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1. Jerzy CHUDORLIŃSKI, 2. Aleksander LISOWIEC, 3. Grzegorz SADKOWSKI, 4. Jakub CHUDORLIŃSKI

ORCID: 1. 0000-0001-6840-3912; 2. 0000-0002-4488-179X 3. 0000-0002-0723-7129 4. 0009-0009-5479-9843

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Metrology of digital instrumentation of power substations

Metrologia cyfrowego oprzyrządowania podstacji elektroenergetycznych

Abstract: *Energy transformation involving distributed renewable energy sources imposes new requirements on the control and measurement equipment of modern power substations. Equipment that meets these requirements includes measuring transformers with a digital interface and SAMUs (Stand Alone Merging Units). Such systems, used to bill prosumers for electricity, must be calibrated. This article describes the requirements for these systems and presents research results and an assessment of measurement errors.*

Streszczenie: *Transformacja energetyczna z udziałem Rozproszonych Źródeł Energii OZE narzuca nowe wymagania na wyposażenie kontrolno-pomiarowe będące na wyposażeniu nowoczesnych podstacji elektroenergetycznych. Wyposażeniem spełniającym te wymagania są przekładniki pomiarowe z interfejsem cyfrowym oraz jednostki scalające SAMUs. Takie systemy, służące do rozliczenia prosumentów za energię elektryczną muszą być wzorcowane. W artykule opisano wymagania dla tych systemów oraz przedstawiono wyniki badań i ocenę błędów pomiarowych.*

Keywords: IEC 61850, digitalization of power substations, digital instrument transformers, SAMU, sampled values SV
Słowa kluczowe: IEC 61850, cyfryzacja rozdzielnic elektroenergetycznych, przekładniki cyfrowe, SAMU, wartości próbkowane SV

Introduction

Recently, there has been a rapid increase in the share of distributed renewable energy sources in the overall energy balance of the power system, which results in a reduction in grid inertia. A stable power system requires large, centralized generating units that can coordinate closely to stabilize the grid frequency. Traditionally, large synchronous generators enable voltage and frequency stabilization due to their high inertia. Transforming electricity generation towards renewable energy sources (RES) requires the implementation of new technical solutions and the revision of existing ones. Power networks require measurement, control, and monitoring systems capable of operating in real time. Such systems must ensure grid protection as well as accurate billing of prosumers for the energy supplied to and consumed from the grid. Digital instrumentation is increasingly replacing analog devices in substations, many of which are approaching the end of their service life. Digital measuring equipment requires the development of new metrological infrastructure for monitoring measurements and calibrating digital substation instrumentation, such as digital output instrument transformers and Stand Alone Merging Units (SAMUs). SAMUs aggregate electrical information from instrument transformers and make it available as a stream of digital Sampled Values (SV). According to the new 2020–2030 guidelines for research, development, and innovation by the European Network of Transmission System Operators for Electricity (ENTSO-E), the digitization of switchgear is one of the structural trends identified as having an impact on the European power system. A key component of this vision is the "digital-enabled substations of the future." The European Metrology Network for Smart Electricity Grids (EMN SEG), coordinated by EURAMET, has identified digital substations as one of its key priorities in its strategic research agenda.

It was therefore necessary to develop methods for calibrating measuring equipment with digital output used in power substations. The research challenge described in the article was to check how manufacturers of equipment with a digital measurement interface can maintain the accuracy class of their equipment and how the measurement accuracy of the measured signals can be assessed by calibration bodies, which required the development of special measurement setups and methods for assessing measurement uncertainty.

Measurement equipment in power substations

Power substations are fundamental components of every electrical power supply system. The proper selection of switchgear bays and control and measurement equipment ensures the safe operation of the entire substation and the continuity of power supply while maintaining the basic parameters of power quality. Energy distribution is carried out through high-, medium-, and low-voltage switchgear (HV, MV, and LV). For example, medium-voltage (MV) switchgear includes a busbar system mounted on insulators and is equipped with switching devices (circuit breakers – CB, disconnectors – DS, earthing switches – ES), instrument current transformers (CTs), voltage instrument transformers (VTs), as well as mechanical interlock and protection systems.

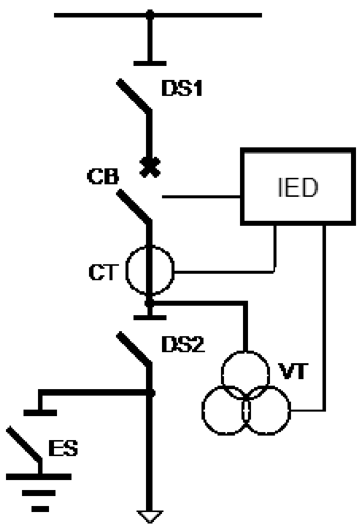

Fig. 1. Single-line diagram of a feeder bay

A typical view of a switchgear bay [1] is presented in the single-line diagram in figure 1. The switchgear is divided into sections called bays. Depending on their function and equipment, these bays are classified as incoming, bus coupler, measuring, or outgoing bays. For control, monitoring, and protection purposes, IED (Intelligent Electronic Device) devices are used. They monitor the operation of the switchgear bay through secondary circuits.

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Information about busbars currents and voltages is obtained from instrument transformers.

Normative requirements for digital substation instrumentation

To standardize the transmission of analog signal data in digital form, a series of standards from the IEC 61869 and IEC 61850 families has been developed. The digitization of measurement signals helps reduce costs, primarily by eliminating unnecessary wiring, which was fundamental to the operation of IED devices in analog substations. In digital substations, data is transmitted via Ethernet links forming the so-called process bus and delivered to the target device through a network switch system. Digital samples of analog signals are referred to, in commonly used English terminology, as Sampled Values (SV). These digital samples are time-stamped based on the UTC time scale. For this reason, devices such as Stand-Alone Merging Units (SAMUs) must be provided with a time synchronization signal, e.g., a 1PPS pulse from a GPS receiver. Digital substation instrumentation solutions provide sampling of current and voltage values in accordance with IEC 61869 and transmission via Ethernet or fiber optic links in compliance with IEC 61850 [2]. The IEC 61869-9 [3] standard describes the requirements for the digital interface of measurement transformers, while IEC 61869-13 [4] specifies requirements for the SAMU unit, which transmits sampled SV signals within a single Ethernet frame. The IEC 61869-9 [3] standard also defines the structure of SV streams transmitted on the process bus. However, the IEC 61850-9-2 [2] standard is considered too general. Therefore, protection device manufacturers have developed a guideline to IEC 61850-9-2 [5], which serves as a recommendation for the presentation and transmission of sampled value streams. Two sampling rates were adopted: 80 samples per cycle for protection purposes and 256 samples per cycle for measurement purposes. This guideline precisely defines the format of data in frames: 3 phase current measurements and the zero-sequence current (I0), as well as 3 phase voltage measurements and the zero-sequence voltage (U0). It also specifies parameters such as the stream name, data type, and the number of sample structures (ASDUs) in a single frame. This has significantly simplified communication between devices from different manufacturers. SV-distributing devices are identified in the network by their MAC address.

Instruments transformers

To assess the parameters of the power supply network in substations, standardized current and voltage instrument transformers are commonly used. Current instrument transformers (CTs) can have an analog output with a nominal current of 1 A or 5 A. There are also low-power current transformers (LPCTs) with a rated secondary voltage of Usr = 22.5 / 150 / 225 mV, compliant with IEC 61869-6 and IEC 61869-10. Voltage instrument transformers (VTs) can have an analog output with a nominal secondary voltage of 100 V/√3, or 3.25 V/√3 in the case of low-power voltage instrument transformers (LPVTs) in accordance with IEC 61869-6 and IEC 61869-11.

Digital Interface of instrument transformers

In modern power substations, instrument transformers with digital interface are increasingly being used. Analog measurement signals are sampled and transmitted in digital form using the SV (Sampled Values) standard over the substation's Ethernet network. The IEC 61850-9-2 [2] standard defines how this data is presented in an Ethernet frame. The value of a single sample is stored in a 32-bit register, with the most significant bit used to indicate signal polarity. The analog measurement values in the samples always refer to the primary side of the instrument transformer. According to the standard, the resolution for phase currents (If) and earth fault currents (I0) is 1 mA, while for phase voltages (Uf) and zero-sequence voltage (U0) it is 10 mV. The ranges of measurement data that can be transmitted under IEC 61850-9-2 [2] are presented in table 1.

Table 1. Range of measurement data transmittable under IEC 61850-9-2 standard

Measured electrical quantity	Maximum transmittable value	Minimum value (bit LSB)
Current	2147 kA peak 1518 kA rms	1 [mA]
Voltage	21475 kV peak 15185 kV rms	10 [mV]

The nominal values of current and voltage must be selected so that, in the 32-bit word, at least the two least significant bits fall below the value corresponding to the accuracy class of the instrument transformer. For current measurements, a multiple of 65 times the rated current (65 In) should be assumed to account for fault current measurements. For voltage measurements, a 2.5 times increase of the rated voltage (2.5 Un) should be considered.

Stand-Alone Merging Unit SAMU

Measurement signals from current and voltage instrument transformers are fed into a Stand-Alone Merging Unit (SAMU), which converts them into digital data in the SV format and then transmits them to the process bus in accordance with the IEC 61850-9-2 [2] protocol, as shown in figure 2.

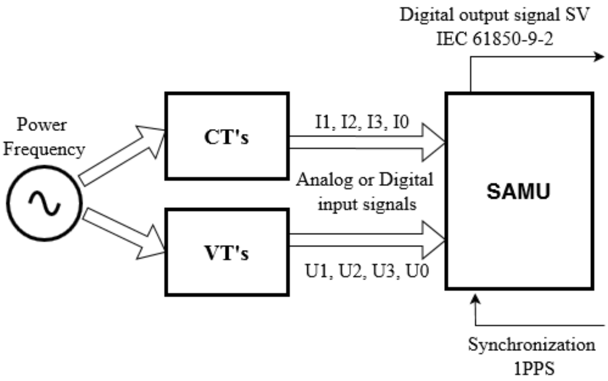

Fig. 2. Example of a digital interface in power substations

To determine the time relationships between signals, a 1PPS signal synchronized to the UTC time scale must be supplied to the time synchronization input of SAMU devices. A device with an interface that transmits SV streams in accordance with IEC 61869-9 [3] must be capable of configuring data streams in compliance with IEC 61850-9-2 [2]. The SAMU device can be configured to generate frames defined by various applicable standards and implementation guidelines for digital SV communication. To facilitate interoperability, only limited variations in naming, message structure, sampling rate, analog signal content, and scaling are permitted. Permitted variants for specifying the capabilities of the integration unit are described using human-readable text notation (frames) **F*f* S*s* I*i* U*u*** [3], where:
f – sampling frequency expressed in samples per second,
s – number of ASDU (Application Service Data Units) in each

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frame,
i – number of current channels in each ASDU,
u – number of voltage channels in each ASDU.

SV data stream frames are defined and described in the IEC 61869-9 [3] standard, for example:
• F4000S1I4U4 for 50 Hz – 80 samples per cycle,
• F4800S1I4U4 for 60 Hz – 80 samples per cycle.
ASDU stands for Application Service Data Unit, used for transmitting information between IED devices and substation monitoring systems.

Permissible measurement error in the digital interface related to the SV data stream

The requirements specified in the IEC 61869-13 standard [4] and publications [6, 8, 9] define the permissible limit error and phase displacement introduced by the SAMU device. The instrument class is determined within a measurement range expressed as a percentage of the nominal value. The measurement range is defined between K_{Imin} and K_{Imax}, where K_{Imin} = 2; 5; 10 [%], and K_{Imax} = 120; 200; 400 [%]. K_{Imin} and K_{Imax} indicate the dynamic measurement range and are specified by the device manufacturer. A value of 100 percent corresponds to the rated current of the device. The permissible measurement error and phase displacement for a class 0.2P SAMU across the full range from K_{Imin} to K_{Imax} are presented in table 2.

Table 2. Permissible Measurement Error and Phase Displacement for Class 0.2P SAMU

SAMU Class	Maximum permissible measurement error relative to the rated current In			
	K_{Imin}/4*In e.g. 0.02* In/4	K_{Imin}*In e.g. 0.02*In	100% In	K_{Imax} e.g. 4 * In
0,2	±0.4%	±0.2%	±0.2%	±0.2%
	Maximum permissible phase displacement error relative to the rated current Ip			
	±20 min	±10 min	±10 min	±10 min

Evaluation of the metrological parameters of SAMU

The aim of the research was to calibrate commercial Stand-Alone Merging Units (SAMUs). ARTECHE SAMU class 0.2 was used for the tests [12]. Two measurement setups were prepared: one for measuring voltage ratio and phase errors (shown in figure 3), and another for measuring current ratio and phase errors (shown in figure 4). The source of the voltage and current signals was the CMC356 Omicron calibrator, selected for its ability to synchronize its internal time using a PTP time server via a 10 MHz signal. Analog signals were simultaneously fed to the measurement inputs of the SAMU under calibration and to one input of the reference measuring bridge. The digital signal from the SAMU under test was connected to the second SV digital input of the reference device. The time server signal was distributed to all devices in the test setup using an Omicron PTP time converter Ticro 100, which allows transmission of both 1PPS and 10 MHz signals. The reference device for the tested SAMU was the WM3000U measuring bridge, used in both the voltage and current setups due to the lack of a dedicated current version. In the current measurement setup, to obtain a voltage signal (necessary as a reference input for the WM3000U bridge), precision measurement resistors (Fluke A40B shunts) were used. A suitable shunt was selected for each current value. The uncertainty budget was based on the specified maximum errors of the reference devices, i.e., the measuring bridge and the shunts. As shown in figure 3, the voltage from the voltage source was supplied in parallel to all three voltage phases of the SAMU under calibration and to the voltage terminals of the measuring bridge. In the setup shown in figure 4, the current from the current source was applied in series to all three current phases of the SAMU and to the shunt, from which the voltage was fed into the measuring bridge. The measuring bridge displays the ratio error (in percent) and the phase error (in minutes of arc), calculated using formulas (1) and (2). The measurement results are presented in tables 3 and 4 and they confirm that the calibrated device meets the 0.2 accuracy class.

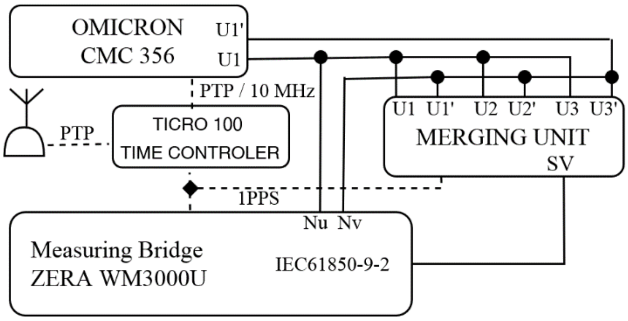

Fig. 3. Measurement setup for evaluating the measurement error of the voltage channels of the SAMU

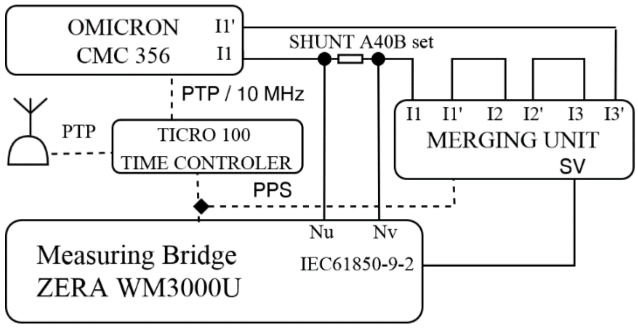

Fig. 4. Measurement setup for evaluating the measurement error of the current channels of the SAMU

The current or voltage ratio error is calculated using formula (1):

$$\varepsilon = \frac{A_X - A_N}{A_N} 100\% \tag{1}$$

where:
ε - ratio error,
A_X – amplitude of the current or voltage signal reconstructed from SV samples,
A_N – amplitude of the reference analog current or voltage signal.
The phase displacement $\Delta\varphi$ is defined according to formula (2):

$$\Delta\varphi = \varphi_X - \varphi_N \tag{2}$$

where:
$\Delta\varphi$ - phase displacement
φ_X – phase displacement of the signal reconstructed from SV,
φ_N – phase displacement of the reference signal.

The uncertainty budgets presented in tables 5 and 6 were compiled in accordance with the guidelines of the good practice guide [7] and EA-04/02 M:2022 *"Evaluation of the Measurement Uncertainty"* [11], which specify the confidence

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levels for coverage factors: k = 1 which corresponds to 68% and k = 2 which corresponds to 95%. The tests were carried out in the range from 1% to 200% of the rated current and from 80% to 120% of the rated voltage.

Table 3. Measurement results of ratio errors and phase displacements for the three phase voltages of the tested SAMU

U/U_N [%]	Line 1		Line 2		Line 3	
	ε [%]	Δφ [min]	ε [%]	Δφ [min]	ε [%]	Δφ [min]
120	-0.011	-7.6	-0.003	-8.0	0.001	-7.9
100	-0.017	-6.3	-0.003	-6.6	-0.006	-6.5
80	-0.027	-4.7	-0.013	-5.0	-0.014	-4.8

Table 4. Measurement results of ratio errors and phase displacements for the three phase currents of the tested SAMU

I/I_N [%]	Line 1		Line 2		Line 3	
	ε [%]	Δφ [min]	ε [%]	Δφ [min]	ε [%]	Δφ [min]
200	0.022	-4.2	0.020	-0.2	0.019	0.9
120	0.020	-4.2	0.021	0.2	0.022	1.1
100	0.021	-3.9	0.019	-0.1	0.019	1.0
20	0.056	-3.7	0.044	0.4	0.043	1.1
5	0.142	-3.4	0.158	0.6	0.092	1.3
1	0.013	-3.4	0.129	0.7	0.035	1.7

Figure 5 shows the measurement setup for testing the SAMU. It shows the previously discussed devices shown (see Fig. 3 and 4) and the tested SAMU device.

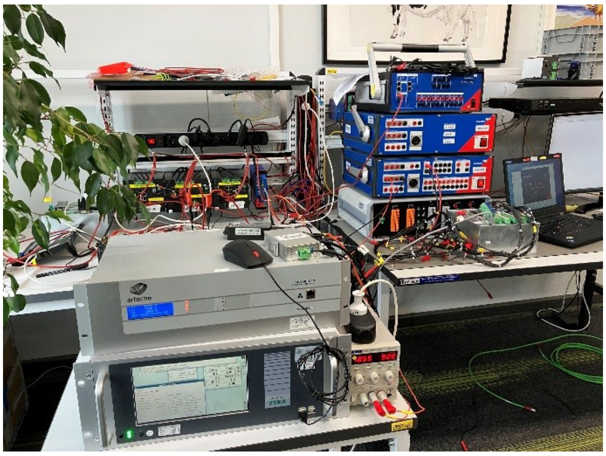

Fig. 5. Measurement setup for testing the SAMU

Table 5. Uncertainty budget for ratio errors and phase displacements in voltage measurements

Uncertainty components	Distribution type	ε [%]	Δφ [min]
Standard deviation of the mean	Normal	0.0001	0.0
Limit error of the WM3000U bridge	Rectangular	0.0115	0.9
Standard uncertainty	k=1	0.012	0.9
Expanded uncertainty	k=2	0.023	1.7

Table 6. Uncertainty budget for ratio errors and phase displacements in current measurements

Uncertainty components	Distribution type	ε [%]	Δφ [min]
Standard deviation of the mean	Normal	0.0001	0.0
Limit error of the WM3000U bridge	Rectangular	0.0115	0.9
Limit error of the shunt set type A40B spec. (Resistance + ACDC transfer)	Rectangular	0.0022	0.2
Standard uncertainty	k=1	0.012	0.9
Expanded uncertainty	k=2	0.024	1.8

The expanded measurement uncertainty of the setup consisting of the WM3000U bridge and shunts was 0.024% for the ratio error measurement and 1.9 minutes for the phase angle error. The measurement results confirmed the class of the calibrated device at 0.2%.

Summary
The article discusses the importance of digitalization of power stations in order to ensure the stability of the power system with high participation of RES. It discusses the requirements of IEC 61850 and IEC 61869 standards for digital instrument transformers and SAMU units, which convert analog signals into SV data transmitted in real time. The measurement setup and measurement results are presented along with the estimation of ratio errors and phase displacements in the tested SAMU device, confirming its compliance with normative requirements and its suitability for use in modern digital substations. The described measurement setup and method are sufficient to determine current and voltage measurement accuracy.

References and Authors

Authors: *M.Sc. Eng. Jerzy Chudorliński, Łukasiewicz Research Network – Tele and Radio Research Institute, ul. Ratuszowa 11, 03-450 Warsaw, E-mail: jerzy.chudorlinski@itr.lukasiewicz.gov.pl; PhD. Aleksander Lisowiec, Łukasiewicz Research Network – Tele and Radio Research Institute, ul. Ratuszowa 11, 03-450 Warsaw, E-mail: aleksander.lisowiec@itr.lukasiewicz.gov.pl; M.Sc. Eng. Grzegorz Sadkowski Central Office of Measures, ul. Elektoralna 2, 00-139 Warsaw E-mail: grzegorz.sadkowski@gum.gov.pl, M.Sc. Eng. Jakub Chudorliński, Łukasiewicz Research Network – Tele and Radio Research Institute, ul. Ratuszowa 11, 03-450 Warsaw, E-mail: jakub.chudorlinski@itr.lukasiewicz.gov.pl.*

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REFERENCE

[1] Hołdyński G., Skibko Z., Medium voltage switchgear equipment elektro.info 5/2019
[2] PN-EN 61850-9-2:2012 Communication networks and systems for power utility automation - Part 9-2: Specific communication service mapping (SCSM) - Sampled values over ISO/IEC 8802-3
[3] PN-EN IEC 61869-9:2019-10, Instrument transformers - Part 9: Digital interface for instrument transformers
[4] PN-EN IEC 61869-13:2021-12, Instrument transformers - Part 13: Stand-alone merging unit (SAMU).
[5] Implementation guideline for digital interface to instrument transformers using IEC 61850-9-2, UCA International User Group, 2004
[6] Szewczyk M., Standard requirements for systems realizing synchronous measurements in the power system infrastructure, Przegląd Elektrotechniczny, ISSN 0033-2097, R. 90 NR 3/2014 doi:10.12915/pe.2014.03.16
[7] Jäschke Ch., Mohns E., Mortara A., Houtzager E., Ayhan B. ENG 61 – Future Grid, May 2017 – Future Grid Good Practice Guide Recommendations related to the calibration and testing of non-conventional current and voltage sensors
[8] Vundekari E.,Rokkam V., Pamulaparthy B. Digital Substation Evolution in the Journey of Smart Grid, Power Research Vol. 16(1)/9-17 2020 DOI: 10.33686/pwj.v16i1.152769

This article has been accepted for publication in Przegląd Elektrotechniczny. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI:10.15199/48.2025.11.34

[9] Alessandro Mingotti A., Costa F., Peretto L., Tinarelli R., Characterization Procedure for Stand-Alone Merging Units Based on Hardware-in-the-Loop Technology, Energies 2021, 14, 1993. https://doi.org/10.3390/en14071993
[10] Skoczykłoda P., Sobczak M., Trzcionka S. Digital Station, XXIV National Conference 2022 "Relay Protection in the Power Industry"
[11] European co-operation for Accreditation (EA), EA-4/02 M:2022 – Evaluation of the Uncertainty of Measurement in Calibration, 3rd Edition, April 2022. https://www.enac.es/documents/7020/635abf3f-262a-4b3b-952f-10336cdfae9e
[12] https://www.arteche.com/en/iec61850-merging-unit-sdo-mu