IEC 61850-9-2, IEC 61850-9-2 LE, IEC 61869-9 and their impact on disturbance recording in digital substations

Alexander Apostolov

OMICRON electronics, USA

1 Introduction

IEC 61850 has been used for more than 10 years and we already have thousands of digital substations in service all over the world. It brings significant benefits, such as improvements in the reliability, security and efficiency of the operation of electric power systems under different conditions.

One of the characteristics of this digitized substations world is the use of sampled values for disturbance recording. The different process interface devices in the digital substation digitize the current and voltage signals and publish streams of sampled values as defined in the IEC 61850 standard. Different devices that are part of the substation protection, automation and control system subscribe to them and use them as required by their functionality.

The goal of this paper is to analyze the components of a disturbance recording system in a digital substation and determine how the evolution of the sampled values communications impacts the disturbance recording.

2 Disturbance Recording Systems

The recording of electric power system events or disturbances is one of the most important tools available to protection and control engineers. Disturbances are always the result of a sequence of events. The analysis of the events and how they end in a local or wide area disturbance is possible only if we have all the information necessary to get the complete picture:

- The settings of the protection IEDs
- The system topology and how it changes with time at the different stages of the disturbance
- The recording of the system parameters during the events and the resulting disturbance

This is why we need the recordings that can be of several different types:

- Transient recordings
- Disturbance recordings
- Event recordings

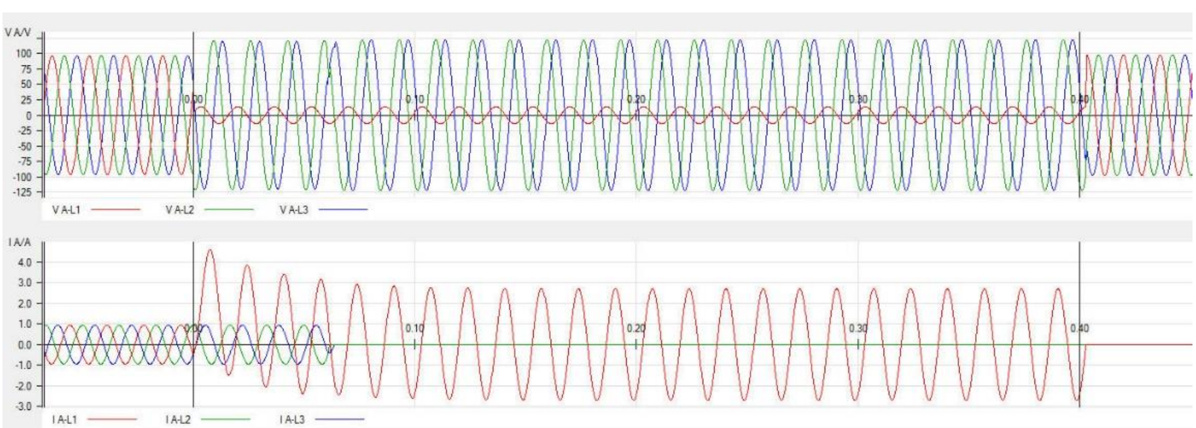

Fig. 1 Single-phase-to-ground fault waveform recording

Transient or waveform recording is available in many multifunctional protection and control IEDs. It captures the individual samples of the currents and voltages measured by the IED with a sampling rate that may be in the hundreds of samples per cycle for high-end monitoring and recording IEDs.

The user typically has options to define the triggering criteria, the pre-trigger or post-trigger intervals and if extended recording should be available in cases of evolving faults or other changing system conditions. The capture of several cycles of pre-fault data, as well as the ability to record the waveform over a period of several seconds will result in better use of the record.

Transient recording also may be performed by dedicated disturbance recording devices with multiple hardwired analog and binary inputs.

The trigger for waveform recording can be local or external. An internal trigger can be based on measured or instantaneous values and in some cases may use superimposed components of the current and voltage signals.

High-speed or low-speed disturbance recording is intended for capturing events such as local or wide area disturbances following short circuit faults on the transmission or distribution system as shown in Figure 2.

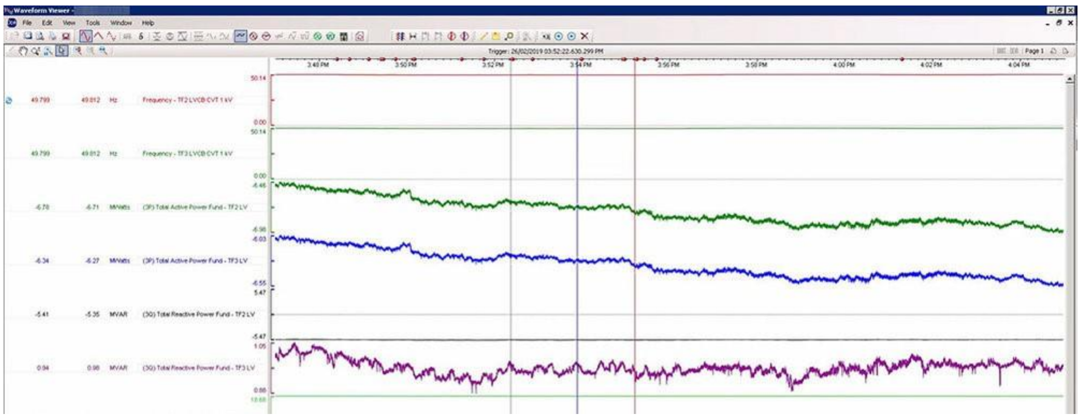

Fig. 2 Disturbance recording

The disturbance recording IED stores the values of a user-defined set of parameters for a period of time that is too long for capturing using sampled values. The setting range is dependent on the available memory in the IED. If the sampling rate is more than one cycle per sample, the user should be able to select the recording of minimum, maximum and average values through the specified sampling interval.

The recorded values can be RMS values, phasors or synchrophasors, depending on the capabilities of the recording device and the requirements of the application.

Recently the IEEE PES PSRC Committee defined a schema that allows the use of COMTRADE files for synchrophasors based disturbance recording.

Event recording is typically performed by the protection IED end includes time-stamped information about the values of the pre- fault, fault and post-fault currents in voltages, as well as which protection elements operated during the event. The IEEE PES PSRC Committee defined a standard C37.239 - IEEE Standard Common Format for Event Data Exchange (COMFEDE) for Power Systems that allows its use for event recording.

3 Process Interfaces in Digital Substations

The digital transformation of the electric power grid based on the development of the IEC 61850 standard created a new range of opportunities for the implementation of disturbance recording in digital substations. Moving the digitization of the current and voltage signals from the analog circuits of the multifunctional IEDs to devices in the substation yard allows the implementation of the recording not only in the IEDs themselves, but also in a centralized server at the substation level.

The digitization of the current and voltage signals in the substation yard can be performed using several different methods.

Low-power instrument transformers (LPIT) may have a low-voltage analog interface which was is not very useful for protection applications. That is why with the advancement of communications technology the concept of the Merging Unit – a device with an analog input and digital output was introduced. This changed the interface of the protection and other devices in the substation as shown in Figure 3.

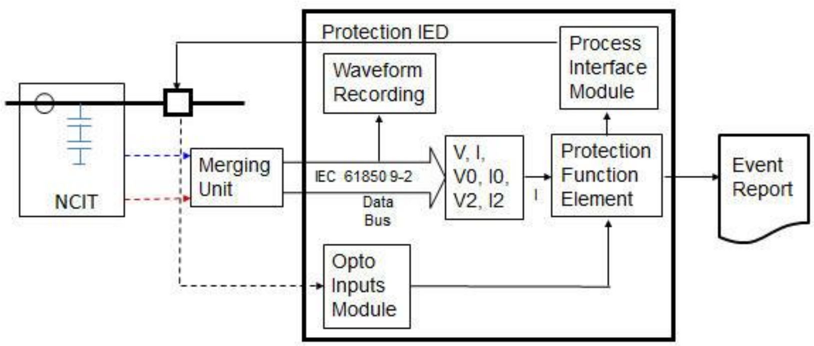

Fig. 3 Low-power NCIT interface

This interface provides all the benefits that are typical for sampled values-based interfaces with multifunctional protection IEDs. Like all other such interfaces it is preferred that the merging unit is located as close as possible to the low-power NCIT output in order to reduce the effect of substation transients on the operation of the protection functions.

Optical CTs, may have direct IEC 61850 sampled values interface as shown in Figure 4.

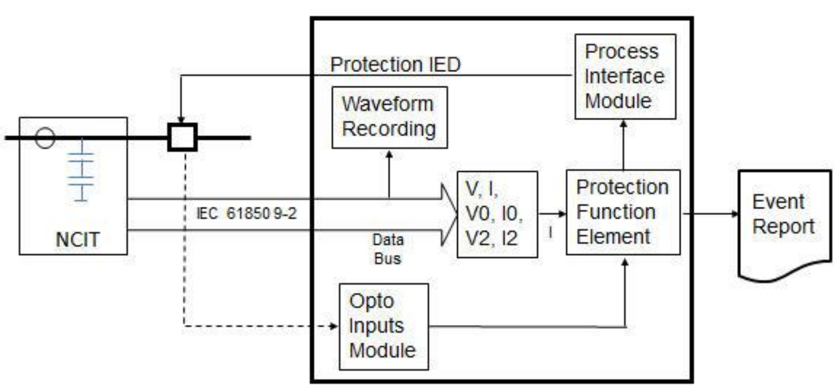

Fig. 4 Direct IEC 61850 9-2 interface

Such an interface simplifies significantly the design of the system, because the number of components of the protection and control system is reduced and the number of interfaces is practically reduced to fiber optic cables only. The single exception is the hardwired connections that power the individual devices.

Considering the requirement for both transient and disturbance recording IEC 61850 based digital substations may use at the bottom of the hierarchy Process Interface Devices (PID) shown in a simplified block diagram in Figure 5.

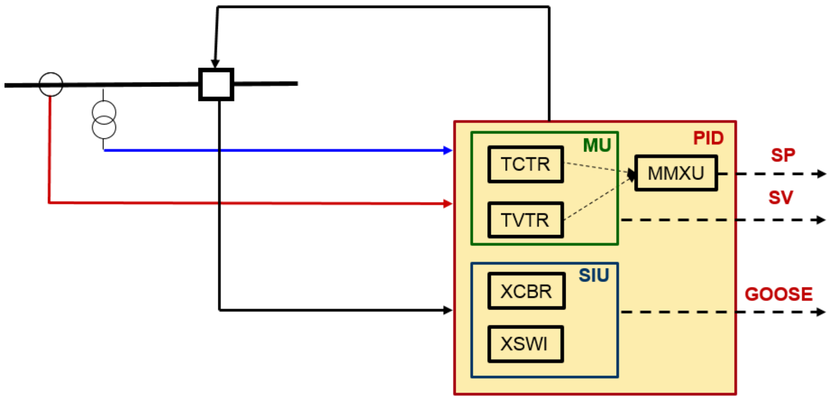

Fig. 5 Process Interface Device

The PID contains two Logical Devices:

- Merging Unit (MU) – it provides the current and voltage interface to the process based on the available interface options described earlier in the paper and publishing sampled values (SV) over the logical process bus to the disturbance recorder or any other substation function.
- Switchgear Interface Unit (SIU) – it provides the GOOSE based interface with the circuit breakers and the disconnector switches as required by the different substation functions, including the disturbance recorder.

The PID may also include local protection or measurement functions, such as an MMXU. Since the PID is accurately time synchronized, it will calculate M or P class synchrophasor measurements and will publish them over the substation LAN as defined in Edition 2 of IEC 61850. These measurements are used for disturbance recording.

The PIDs or PIUs connected to the primary equipment in the substation are communicating with the centralized disturbance recording system as shown in Figure 6.

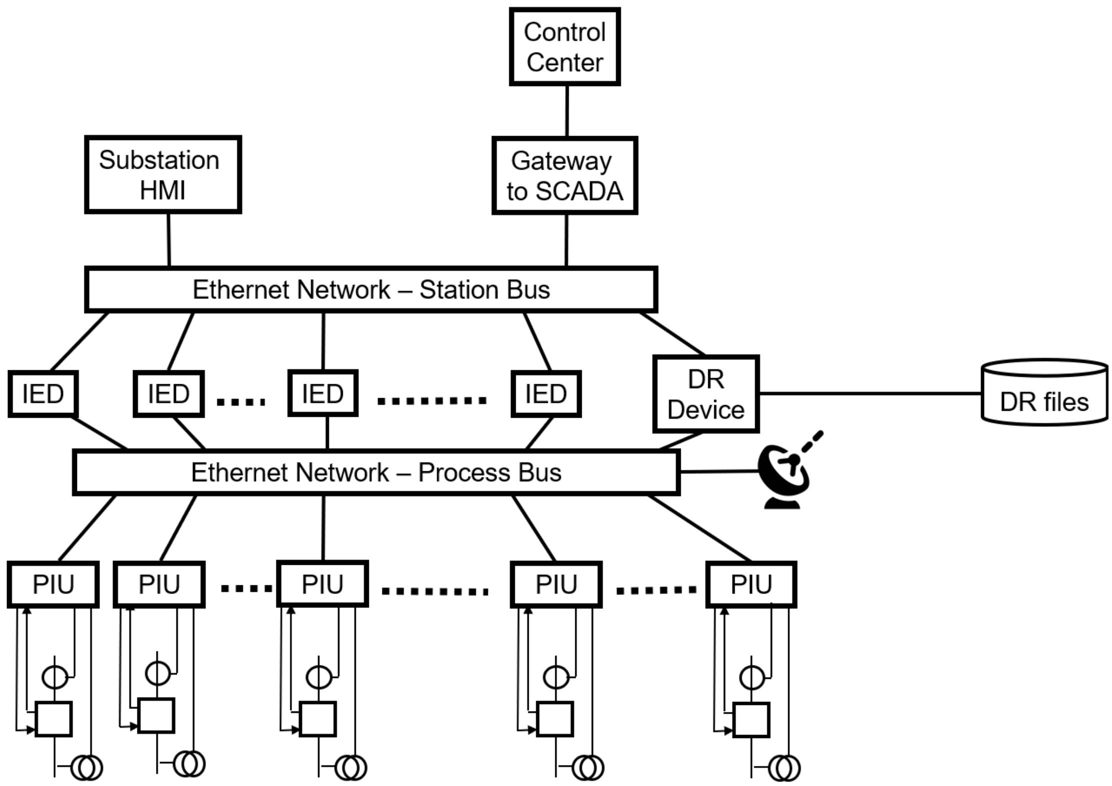

Fig. 6 Disturbance recording system in IEC 61850 based digital substations

4 Sampled values communications

Sampled values are used to represent the digitized current and voltage signals as instantaneous values of voltage and current waveforms, which are critical for protection, control, monitoring and recording of power systems. They were introduced in the IEC 60044-8 standard published in 2002. It focuses on Electronic Current Transformers (ECT) and provides guidelines for the design, testing, and application of these devices. IEC 60044-8 specifies the use of sampled values for representing primary currents in secondary circuits. It was an early attempt to introduce electronic devices into power system protection and control, replacing traditional iron-core current transformers (CTs) and inductive voltage transformers (VTs). The main goal was to improve accuracy and response time, reduce size and weight, and enable new protection functions. This standard laid the groundwork for the development of digital substations that were also made possible based on the abstract modeling concepts of IEC 61850.

Each device is modeled as a server containing different logical devices representing specific functions supported by it. The logical devices contain logical notes representing individual function elements that contain data objects with multiple data attributes.

The devices support various services which behave based on the values in their control block. The sampled values communications are using a peer-to-peer relationship and a publisher-subscriber mechanism. The data exchange between the components of the protection, automation and control system in the substation using these services is based on the use of specific data sets defined during the engineering of the system. An abstract representation of this model is shown in Figure 7.

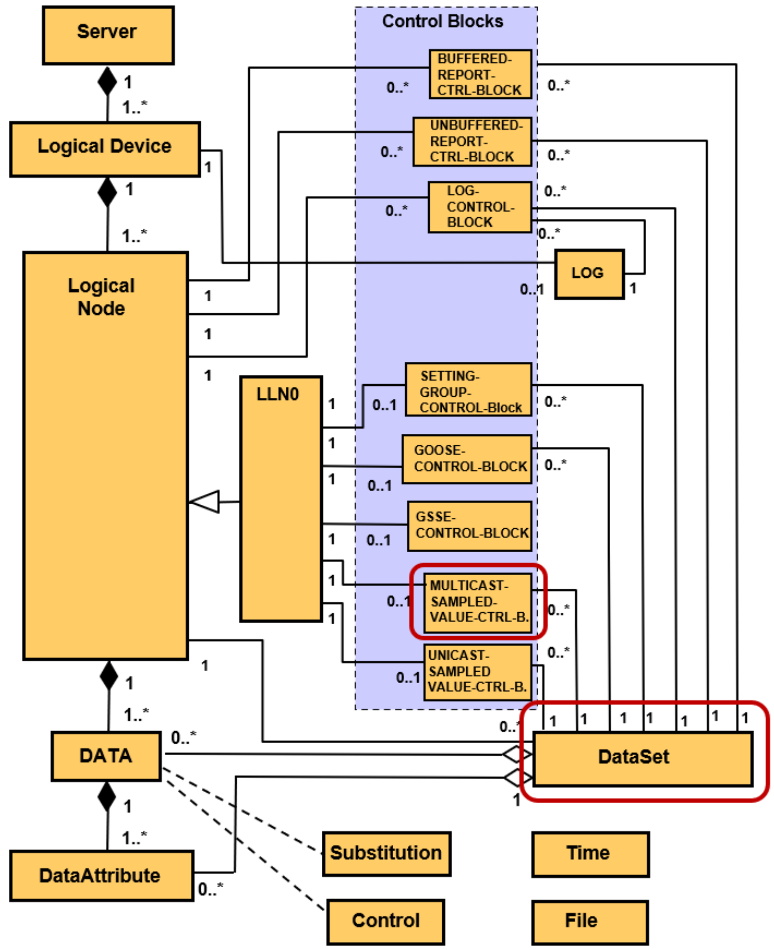

Fig. 7 IEC 61850 abstract object model

4.1 IEC 61850 9-2

IEC 61850-9-2 Edition 1 was published in 2004 as part of the IEC 61850 series defining the mapping of the abstract model defined in part 7 of the standard to ISO/IEC 8802-3. It defines the process bus for communication between Intelligent Electronic Devices (IEDs), merging units, and other equipment in the substation. It provides a standardized method for transmitting sampled values over Ethernet networks, using the IEC 61850-9-2 Sampled Values (SV) protocol. Edition 2 was published in 2011, followed by Amendment 1 in 2020.

The evolution from IEC 60044-8 to IEC 61850-9-2 represents a shift from electronic current transformers to a standardized communication framework for sampled values in digital substations. This transition has significantly improved the interoperability, scalability, flexibility, and functionality of power system protection, control, and monitoring applications. The use of Ethernet-based communication networks allows for better scalability, enabling the deployment of digital substations with a larger number of devices and increased data throughput.

While Edition 1 supported only communications of instantaneous values as multiple samples/cycle at the nominal frequency, Edition 2 supports various types of sampled values, such as instantaneous values, integrated values, and phasor values published as samples per nominal period (DEFAULT), samples per second or seconds per sample. This is one of the configuration parameters in the Sampled Values (SV) control block which defines the transmission of sampled values in digital substations. It is a data structure used to configure, manage, and control the transmission of sampled values from a Merging Unit (MU) to receiving Intelligent Electronic Devices (IEDs). It contains important information allowing the receiving devices to correctly interpret and process the received data, such as:

- svID (Sampled Values Identifier): The svID is a unique identifier for a specific SV control block instance. It helps differentiate between multiple instances of SV control blocks within a single MU or between different MUs in a substation.
- datSet (Data Set Reference): The datSet element points to a data set that contains the actual sampled values (e.g., voltage and current measurements) to be transmitted.
- smpRate (Sampling Rate): The smpRate specifies the rate at which the sampled values are acquired and transmitted by the MU. This is typically expressed in samples per cycle at the nominal frequency
- confRev (Configuration Revision): The confRev represents the revision number of the SV control block configuration. It is used to ensure that all receiving devices are aware of the current configuration and to detect potential configuration mismatches between the sending and receiving devices.
- smpMod (Sampling Mode): The smpMod indicates the mode of sampling employed by the MU. This information is necessary for the receiving IEDs to correctly process the sampled values.
- Multicast Address: The SV control block also includes the multicast address used for transmitting the sampled values over the Ethernet network.

IEC 61850-9-2 defines the Specific communication service mapping (SCSM) for sampled values over ISO/IEC 8802-3 based on the model from IEC 61850-7-2 described earlier. it applies to low power instrument transformers with digital interface or to standalone merging units connected to the low side of conventional instruments transformers. However, it does not specify individual implementations in products.

The communications of sampled values are based on structured data units used for exchanging information between devices in power system automation - APDU (Application Protocol Data Unit) and ASDU (Application Service Data Unit).

An APDU is the highest-level data unit in the communication protocol's application layer. It typically includes both the header and the payload of a message. The header contains information about the message type, addressing, and other control information, while the payload contains the actual data being exchanged, such as measurements, commands, or status information.

An ASDU is a part of the APDU's payload and represents the actual data being exchanged between devices in the network. It contains a specific set of data elements and their associated attributes, such as object type, object address, object value, and quality descriptors. The structure and content of the ASDU depends on the communication protocol being used and the specific application services being implemented

The application layer functionality allows the concatenation of multiple ASDUs in a single APDU depending on the sampling rate required by the applications. Each individual sample data is represented by one ASDU and when multiple ASDUs are concatenated in the single frame the oldest sample is the first one in it.

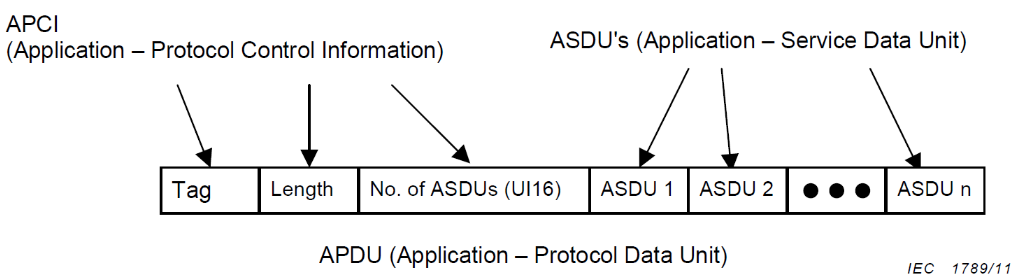

Fig. 8 IEC 61850-9-2 APDU

4.2 IEC 61850-9-2 LE

IEC 61850-9-2 defines the rules for sampled values communications but does not specify the object models of the devices performing the digitization, the sampling rate and the number of ASDUs in an APDU. This is to ensure the flexibility of the standard to meet any specific manufacturer or user requirements. However, the cost of flexibility is interoperability challenges. This was realized quickly by the international experts involved in the development of the standard which led to the creation of a task force to address the interoperability challenge and define a profile of the standard with limited flexibility by defining a specific object model of the digitizing device, as well as the sampling rates and the number of ASDUs in an APDU.

This task was under the UCA International Users Group and its work resulted in the publication of the "Implementation guideline for digital interface to instrument transformers using IEC 61850-9-2" in 2004 which became known as IEC 61850-9-2 LE.

It defined a logical device merging unit containing a number of specific sensor logical nodes, the sampling rates and the dataset used for the transmission

It recommended to use as a physical interface fiber optic 100Base-FX full duplex with ST connectors. 100Base-FX with MT-RJ connectors or electrical transmission using 100Base-TX full duplex with RJ-45 connectors were the only allowed alternatives.

The profile defined a specific logical device "Merging Unit" shown in Figure 9.

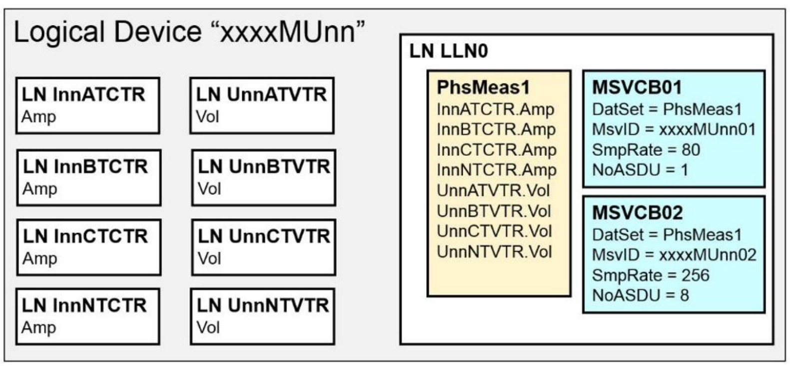

Fig. 9 Logical device "Merging Unit"

Each of the TCTR and TVTR logical nodes digitizes one phase or neutral current or voltage with the primary current and voltage sampled values becoming members of the dataset PhsMeas1 used in the ASDU.

As shown in the figure there are two optional control blocks:

- MSVCB01 with a sampling rate of 80 samples/cycle and a single sample (ASDU)/message
- MSVCB02 with a sampling rate of 256 samples/cycle and 8 samples (ASDU)/message

The profile specifies two nominal frequencies – 50 Hz and 60 Hz. This means that the merging unit manufacturer needs to design devices that will publish 4000 samples/ second when the nominal frequency is 50 Hertz and 4800 samples/second when the nominal frequency is 60 Hertz with 80 samples/cycle at both nominal frequencies.

One pulse per second (PPS) was used to synchronize the sampling of merging units. It supports the required accuracy of 1 microsecond, but it requires a dedicated time synchronization network.

The publication of this implementation guideline became the driving force behind the acceptance of the digitized process interfaces in the substation leading to the development of many fully digital substations based on the IEC 61850 standard all over the world today.

4.3 IEC 61869-9

Today the communications of the sampled values are based on IEC 61850 9-2 LE profile, but in the future this will be replaced by IEC 61869-9: Instrument Transformers - Part 9: Digital interface for instrument transformers developed by IEC TC38 and published in 2016.

This standard defines requirements for digital communications of instrument transformer measurements. It is based on the IEC 61850 series, UCA international users group document Implementation guideline for digital interface to instrument transformers using IEC 61850-9-2, and the relevant parts of IEC 60044-8 that are replaced by this standard. It includes additional improvements including the IEC 61588 network-based time synchronization. It defines two preferred sampling rates:

- 4800 Hz for general measuring and protection applications, regardless of the power system frequency
- 14400 Hz for power quality and metering applications, regardless of the power system frequency

IEC 61869-9 is very similar to IEC 61850-9-2 LE and in order to support interoperability with the large base of existing devices and digital substations devices that are implementing it can be configured to be backward compatible. However, there are a few very significant differences that should be considered in the design and implementation of protection and control systems based on IEC 61869-9 compared to IEC 61850-9-2 LE.

The most critical is the fact that IEC 61850-9-2 specifies the sampling rates of the merging unit as a number of samples / cycle at the nominal frequency while IEC 61869-9 specifies the sampling rate in Hz i.e. the number of samples per second regardless of the nominal frequency.

This allows the same merging unit to be used in a system with either 50 or 60 Hertz nominal frequency. However, the processing of the samples will be different in systems with different frequency because it will correspond to a different number of samples / cycle.

If we take as an example the case with 80 samples per cycle typical for IEC 61850-9-2 LE, at the 60 Hertz system it will correspond to 4800 Hz sampling rate, which is one of the default values in IEC 61869-9, so no change needs to be made in the design of the merging units or the IEDs with this specific sampling rate selected.

However, if the same merging unit is used in a 50 Hertz system the number of samples per cycle will be 96 which will require different processing from what was used in the IEC 61850-9-2 LE based solution.

Another significant difference is in the number of ASDUs per APDU. While for protection applications we have 1 ASDU per message and 8 ASDUs per message for power quality related applications. in the case of IEC 61869-9 for protection applications we have 2 ASDUs per message and for power quality applications with a sampling rate of 14400 Hz we have 6 ASDUs per message. One benefit of this approaches is that for both sampling rates we have the same number of messages per second – 2400 which will result in a significant reduction in the loading of the communications network since the number of messages used for sampled values will be cut in half.

5 Conclusions

The digital transformation of the electric power grid brings significant benefits that improve the reliability, security and efficiency of its operations. One of the key factors contributing to this is the digitization of the analog signals based on sampled values communications defined in the IEC 61850 standard.

The object models of these communications are defined in part 7 of the standard while the actual implementation in devices and systems are based on the mapping defined in IEC 61850-9-2.

The standard is designed to support flexibility in its implementation; however, this leads to some interoperability challenges. That is why a special task force developed a profile known as IEC 61850-9-2 LE which defined the object model of a merging unit as a logical device with its logical nodes and data sets. This implementation agreement created the foundation for the development and implementation of fully digital substations that are in service today all over the world,

The latest development In sampled values communications is the publication of IEC 61869-9 developed by IEC TC 38. IEC 61850-9-2 specifies the sampling rates of the merging unit as a number of samples / cycle at the nominal frequency while IEC 61869-9 specifies the sampling rate in Hz i.e. the number of samples per second regardless of the nominal frequency. This means that the same merging unit can be used in systems with different nominal frequency, however the disturbance recording systems need to process the received sampled values based on the system's nominal frequency.

References

1. IEC 60044-8:2002 Instrument transformers - Part 8: Electronic current transformers
2. IEC 61850-9-2: 2004 Communication networks and systems in substations - Part 9-2: Specific communication service mapping (SCSM) – Sampled values over ISO/IEC 8802-3 was published 2004-04-20.
3. IEC 61850-9-2: 2011 Communication networks and systems for power utility automation - Part 9-2: Specific communication service mapping (SCSM) - Sampled values over ISO/IEC 8802-3, Edition 2 2011-09-22
4. IEC 61850-9-2: 2020 Communication networks and systems for power utility automation - Part 9-2: Specific communication service mapping (SCSM) - Sampled values over ISO/IEC 8802-3, Edition 2 Amendment 1 2020-02-12
5. Implementation guideline for digital interface to instrument transformers using IEC 61850-9-2, UCA International Users Group, 7.7.2004
6. IEC 61869-9:2016 Instrument transformers - Part 9: Digital interface for instrument transformers, 2016-04-27