Disturbance Recording in Digital Substations

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1. Introduction

The IEC 61850 standard for Communication Networks and Systems for Utility Automation allows utilities to consider new designs for substations applicable for both new substation and refurbishments. The levels of functional integration and flexibility of communications based solutions bring significant advantages in costs in all stages of a project. This integration affects not only the design of the substation but almost every component and/or system in it such as protection, control, monitoring and recording by replacing the hardwired interfaces with communication links. The use of high-speed peer-to-peer communications based on Generic Substation Event (GSE) messages and sampled values from non-conventional or conventional sensors allows the development of distributed applications. In addition, the use of optical local area networks leads in the direction of copper-less substations.

IEC 61850 is revolutionizing the substation protection, automation, control, monitoring and recording systems by significantly improving their performance and efficiency. The complete set of benefits of this technology can be achieved with the full implementation of the standard in what is known as "digital substations".

The first part of the paper introduces the concept of the digital substation and describes its components and functional hierarchy.

The second part of the paper discusses the use cases which determine the requirements for disturbance recording:

- Transient fault recording
- Dynamic disturbance recording

The third part of the paper describes the communications architecture of the digital substation and the considerations of the data flow that need to be taken into account.

The impact of several standards on the transient and disturbance recording is discussed later in the paper including:

- IEC 61850 9-2
- IEC 61869-9
- IEC 61850 90-5

2. IEC 61850 Based Digital Substation Functional Hierarchy

A digital substation is a substation where all the interfaces between the primary equipment (the process) and the Substation Protection, Automation and Control System (SPACS), as well as between all the secondary equipment of the SPACS are communications based, using the object models and communications services defined in the IEC 61850 standard.

The development of different functions in the substation protection and control system is possible only when there is good understanding of both the problem domain and the IEC 61850 standard. It does not only define how data is communicated between functions in the substation, but also describes the functionality of the substation in an object-oriented approach. The concept of distributed functions is one of the key elements of the standard that allows for utilities to rethink and optimize their substation designs.

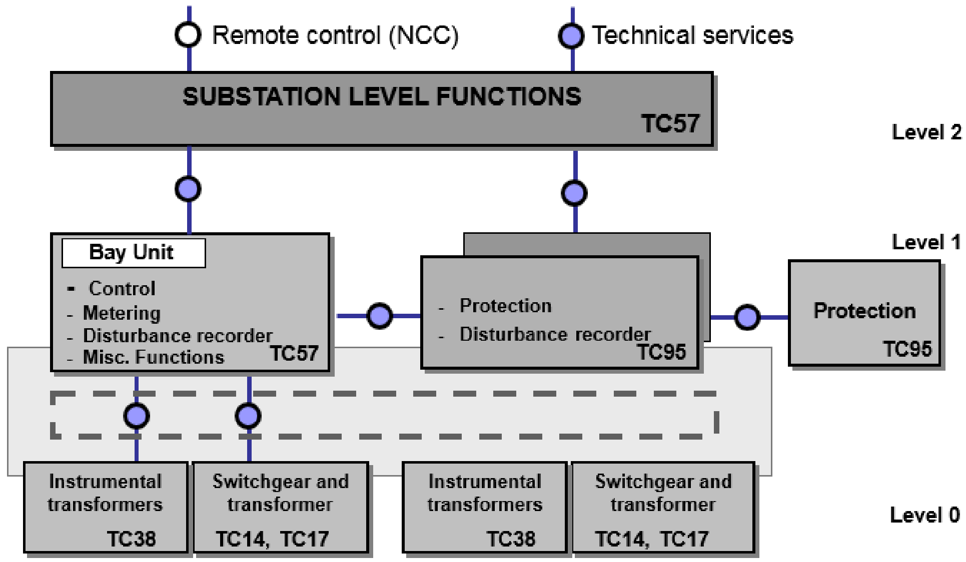

Figure 1: Process Bus definition

A function in an IEC 61850 based integrated protection and control system can be local to a specific primary device (distribution feeder, transformer, etc.) or distributed and based on communications between two or more IEDs over the substation local area network.

IEC 61850 defines several ways for data exchange between IEDs that can be used for different forms of distributed applications. They introduce a new concept that requires a different approach in order to define the individual components of the systems in substations.

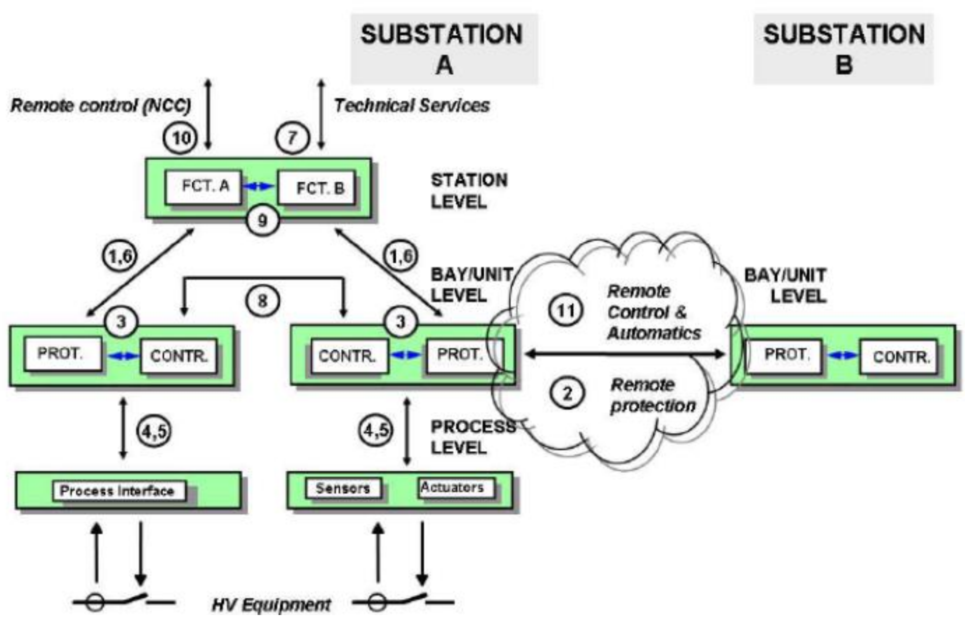

Figure 2: Logical interfaces in IEC 61850

The existing designs are based on hardwired interfaces between the high voltage equipment – transformers, breakers, instrument transformers, etc. and the rest of the substation devices. The interface requirements of many of these devices differ. As a result specific multi core instrument transformers were developed that allow for accurate metering of the energy or other system parameters on the one hand and provide a high dynamic range used by e.g. protection devices.

With the introduction of IEC 61850 several different interfaces (Figure 2) have been defined that can be used for various substation applications using dedicated or shared physical connections - the communications links between the physical devices. The allocation of functions between different physical devices defines the requirements for the physical interfaces, and in some cases may be implemented into more than one physical Local Area Network (LAN).

The functions in the substation can be distributed between Intelligent Electronic Devices (IEDs) on the same, or on different levels of the substation functional hierarchy – Station, Bay or Process. These levels and the logical interfaces are shown by the logical interpretation of Figure 2. The logical interfaces of specific interest to distributed applications based on process bus are defined [1] as:

IF4: CT and VT instantaneous data exchange (especially samples) between process and bay level.

IF5: control-data exchange between process and bay level

IF8: direct data exchange between the bays especially for fast functions such as interlocking

IF8 includes the use of GOOSE messages which can are also required for the interface between the switching devices and the SPACS as part of the Process Bus.

A significant improvement in functionality and reduction of the cost of integrated substation protection and control systems can be achieved using the IEC 61850 based communications as described below.

3. Process Bus Components

Non-conventional instrument transformers with digital interface based on IEC 61850-9-2 [3] (Process Bus) result in further improvements and can help eliminate some of the issues related to the conflicting requirements of protection and metering IEDs.

The interface of the instrument transformers (both conventional and non-conventional) with different types of substation protection, control, monitoring and recording equipment is through a device called a Merging Unit. This is defined in IEC 61850-9-1 as:

“Merging unit: interface unit that accepts multiple analogue CT/VT and binary inputs and produces multiple time synchronized serial unidirectional multi-drop digital point to point outputs to provide data communication via the logical interfaces 4 and 5”.

Existing IEC 61850 Merging Units have the following functionality:

- Signal processing of all sensors – conventional or non-conventional
- Synchronization of all measurements – 4 currents and 4 voltages
- Digital interface –IEC 61850-9-2 LE [3]

The Implementation Guideline for Digital Interface to Instrument Transformers Using IEC 61850-9-2 is a profile which was developed by the UCA International Users Group to insure interoperability between merging units and multifunctional IEDs from different manufacturers. This profiled defined the object model of the merging unit as a logical device with multiple instances of TCTR and TVTR logical nodes, as well as the sampling rates and data sets as shown in Figure 3.

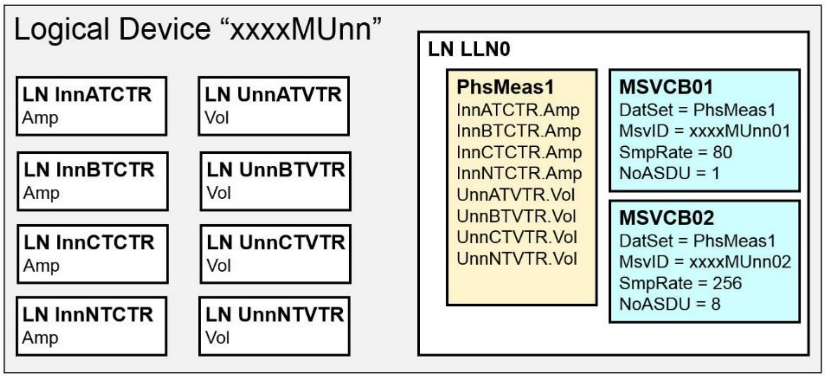

Figure 3: Object model of merging unit according to IEC 61850 9-2 LE

The use of process bus is expected to be further advanced by the availability of the new IEC 61869-9 standard for digital interface of instrument transformers developed by IEC TC 38.

It is important to be able to interface with both conventional and non-conventional sensors in order to allow the implementation of the system in existing or new substations.

The stand-alone Merging unit has similar elements (as can be seen from Figure 4) and can be considered as the analogue input module of a conventional protection or other multifunctional IED. The difference is that in this case the substation LAN performs as the digital data bus between the input module and the protection or functions in the device. They are located in different devices, just representing the typical IEC 61850 distributed functionality.

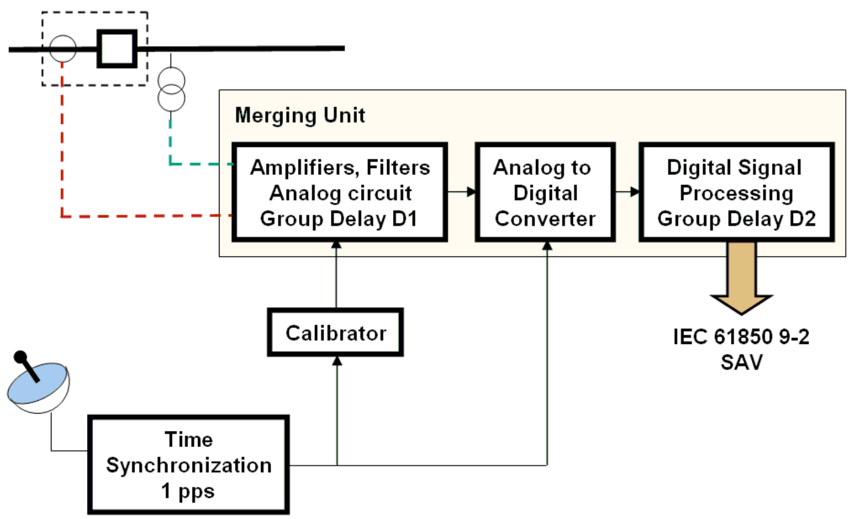

Figure 4: Merging unit

There are several important differences between the data sampling in a microprocessor based relay and the process bus as defined in IEC 61850:

- While in the relays the sampling is controlled by the IED and is usually using frequency tracking, in IEC 61850 all interface or merging units are time synchronized with accuracy better than 1 microsecond and use a fixed number of samples per cycle at the nominal frequency

- The sampled values in the IED are exchanged directly between the A/D converter and the processor, while in IEC 61850 they are transmitted using typically multicast from the merging unit (publisher) to all IEDs (subscribers) that need these sampled values

Interoperability between merging units and protection, control, monitoring or recording devices is ensured through documents providing implementation guidelines. Two modes of sending sampled values between a merging unit and a device that uses the data are defined in IEC 61850 9-2 LE and shown in Figure 3. For protection applications the merging units send 80 samples/cycle in 80 messages/cycle, i.e each Ethernet frame has the MAC Client Data contain a single set of V and I samples. For waveform recording applications such sampling rate may not be sufficient. That is why 256 samples/cycle can be sent in groups of 8 sets of samples per Ethernet frame sent 32 times/cycle [3].

Since SNTP did not provide the required accuracy for the time synchronization of merging units, many of the existing ones are using 1 pps. However, the precision time protocol (PTP) profiles based on IEEE 1588 are the direction in which our industry is going and we are expecting soon to have the merging units being synchronized based on IEC 61850 9-3 Time Protocol Profile for Power Utility Automation [4].

The sampled analog values model applies to the exchange of values of a DATA-SET shown in Figure 3 as PhsMeas1. The difference in this case is that the data of the data set are of the common data class SAV (sampled analogue value as defined in part IEC 61850-7-3). A buffer structure is defined for the transmission of the sampled values that are the output from the multiple instances of logical nodes TCTR and TVTR (Figure 3).

The information exchange for sampled values is based on a publisher/subscriber mechanism. The publisher writes the values in a local buffer at the sending side (see Figure 5), while the subscriber reads the values from a local buffer at the receiving side. A time stamp is added to the values, so that the subscriber can check the timeliness of the values and use them to align the samples for further processing. The communication system shall be responsible to update the local buffers of the subscribers. A sampled value control (SVC) in the publisher is used to control the communication procedure.

The currents and voltages from TCTR and TVTR accordingly are delivered as sampled values over the substation LAN. In this case the network becomes the data bus that provides the interface between the instrument transformer logical nodes and the different logical nodes that are used to model the functional elements of the IED.

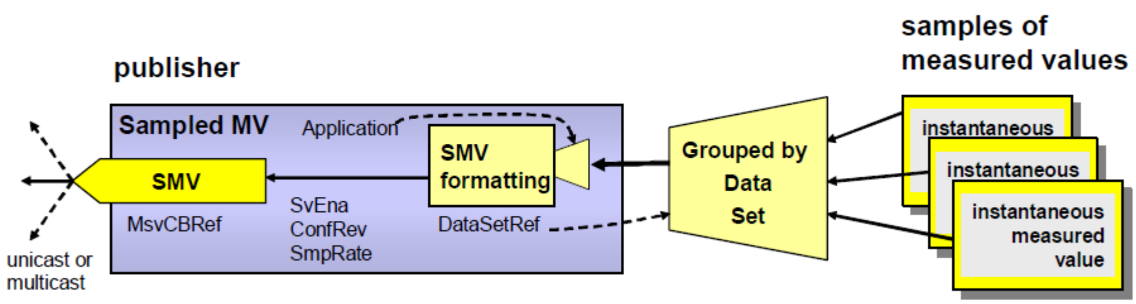

Figure 5: Sampled Analog Values publishing

Depending on the specific requirements of the substation, the user can design it with different communications architectures as described in the next section of the paper.

Because of the requirements for use of IEC 61850 in other domains, such as hydro power plants or distributed energy resources, the concept of process bus is being extended to cover many different non-electrical process interfaces. The functional decomposition for any specific case can be based on the abstract model shown in Figure 8.

The process interface is represented by the LN group T Logical Nodes for instrument transformers and sensors. Their output is Sampled Analog Values that are published over the site's local area network and used by any function element that may need them.

The example in Figure 6 shows logical nodes that may belong on some of the logical node groups defined in IEC 61850 7-4:

- LN group F Logical Nodes for functional blocks
- LN group M Logical Nodes for metering and measurement
- LN group P Logical Nodes for protection functions
- LN group S Logical Nodes for supervision and monitoring

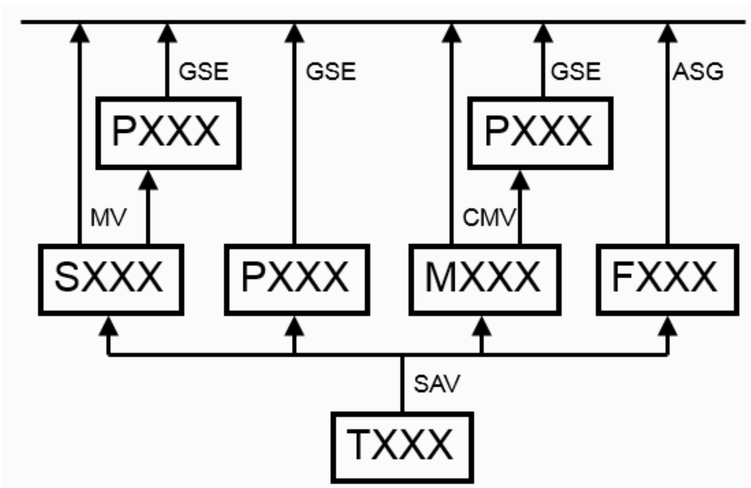

Figure 6: Abstract functional decomposition

The process interface functions are represented by several different logical nodes also defined in IEC 61850 7-4. From the point of view of disturbance recording the ones of interest are:

- LN Current transformer TCTR
- LN Voltage transformer TVTR

The current and voltage sampled values can be used by the different monitoring (SXXX), protection (PXXX) or measurements (MXXX) logical nodes.

Regarding the requirements for disturbance recording the logical node MMXU can be used for the calculation of current and voltage synchrophasors of the P class with a calculation rate of for example 4/cycle which is suitable for the recoding of wide area disturbances by the digital substation's distributed recording system.

The communications of synchrophasors over the digital substation LAN is based on the sampled values publishing mechanism as defined in IEC 61850 90-5.

4. IEC 61850 Architecture

IEC 61850 is being implemented gradually by starting with adaptation of existing IEDs to support the new communications standard over the station bus and at the same time introducing some first process bus based solutions. The specifics of the two types of systems are described in the following two sections of this part of the paper.

Full advantage of all the features available in the standard can be taken if both the station and process bus are used.

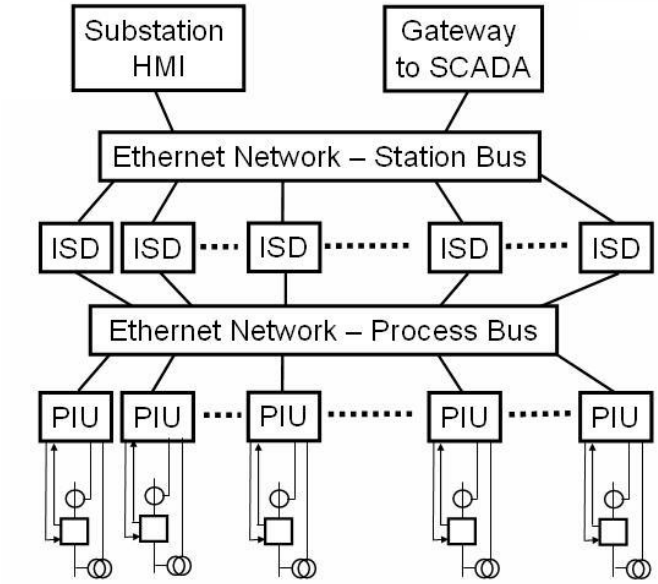

Figure 7: Station and Process bus functional architecture

IEC 61850 communications based distributed applications involve several different devices connected to a substation local area network as shown in the simplified block diagram in Figure 7.

A Merging Unit (MU) or a Process Interface Unit (PIU) will process the sensor inputs, generate the sampled values for the 3 phase currents and voltages, format a communications message and multicast it on the substation LAN.

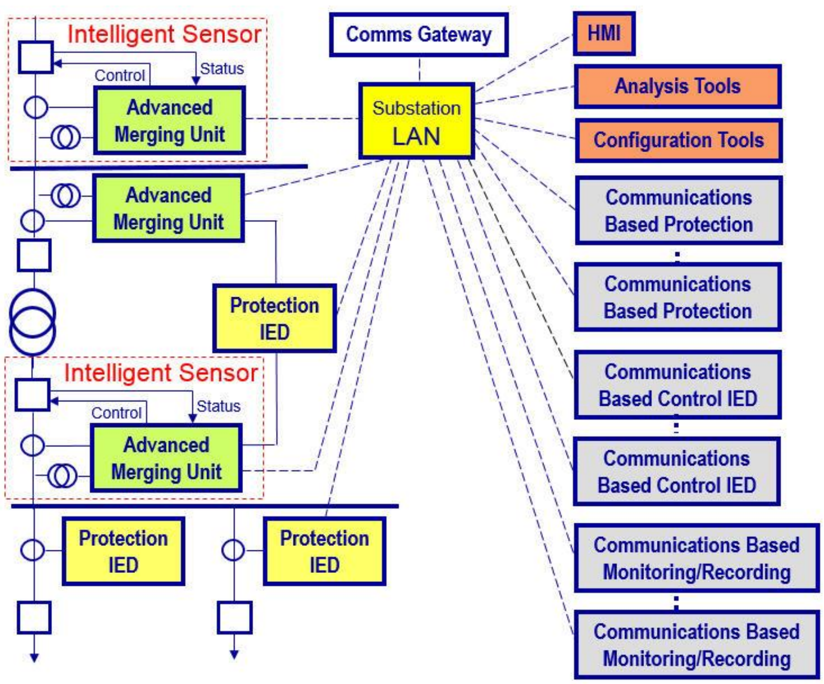

Figure 8: Substation design with Station and Process bus

A binary input/output unit (IOU) can be used to monitor the status of the breaker and trip or close it when necessary based on the GOOSE messages it receives from the different IEDs.

The merging unit and the input/output unit can be combined in a single device – a process interface unit (PIU) as shown in Figure 7 or integrated in IEDs with some local protection functions in PiIEDas shown in Figure 9. The integration of sensor technology with digital interface is the next phase in the development of centralized digital substations as shown in Figure 9.

All multifunctional IEDs will then receive sampled values messages and binary status messages, the ones that have subscribed to this data then process the data (including re-sampling in most of the cases), make a decision and operate by sending a GSE message to the IOU to trip the breaker or perform any other required action.

This is an illustration of how the substation design changes when the full implementation of IEC 61850 takes place. All copper cables used for analog and binary signals exchange between devices are replaced by communication messages over fiber. If the DC circuits between the substation battery and the IEDs or breakers are put aside, the digital "copper-less" substation is a fact.

Further integration of SPACS functions can be achieved by the implementation of a centralized system that will use the 61850 process interfaces defined in the standard and using MMS, GOOSE and SV communications. The system architecture in this case includes several substation computers running a real time operating system with function elements interfacing based on the object models defined in the standard.

Such an approach will accomplish the ultimate functional integration that results in significant savings and improvements in the reliability of the substation protection, automation and control system.

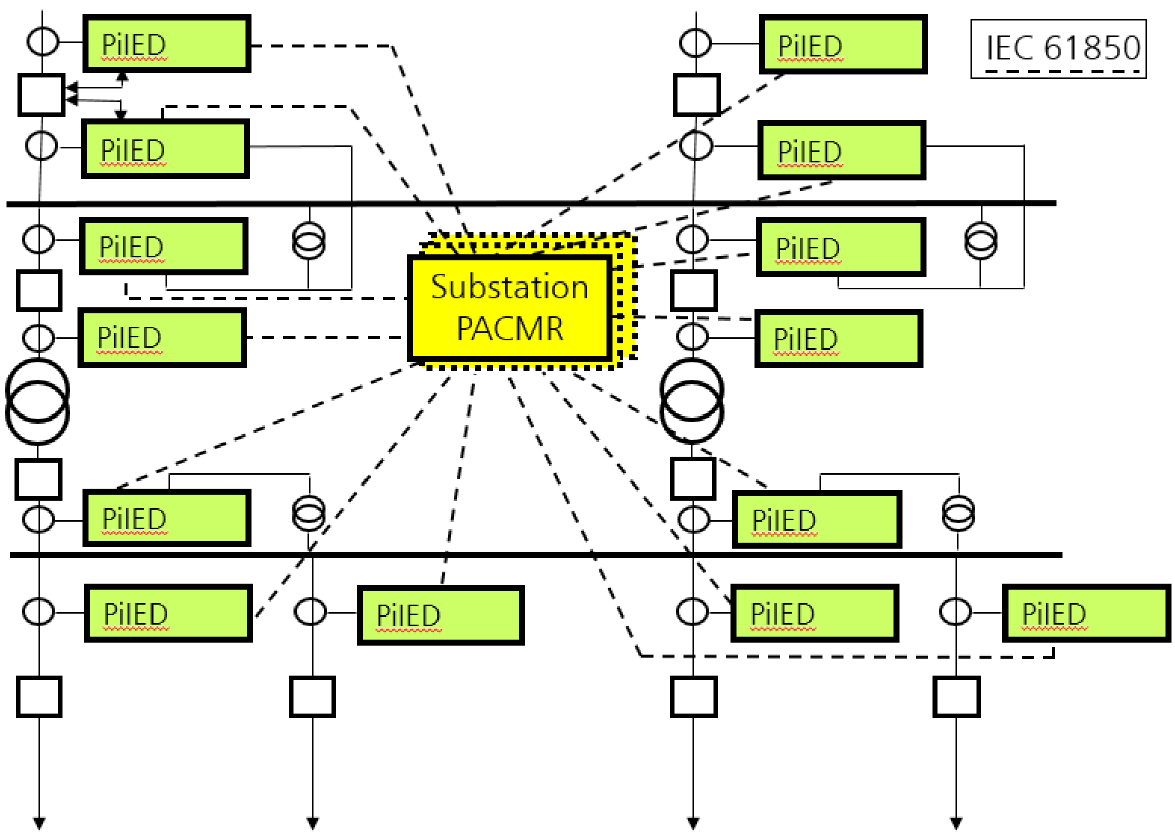

Figure 9: Substation design with centralized SPACS

5. Waveform Recording Based on Sampled Analog Values

Protection, control, monitoring and recording systems perform different functions in a substation. A function can be divided into sub-functions and functional elements. The functional elements are the smallest parts of a function that can exchange data. These functional elements in IEC 61850 are called Logical Nodes.

In the case when a function requires exchange of data between two or more logical nodes located in different physical devices, it is called a "distributed function".

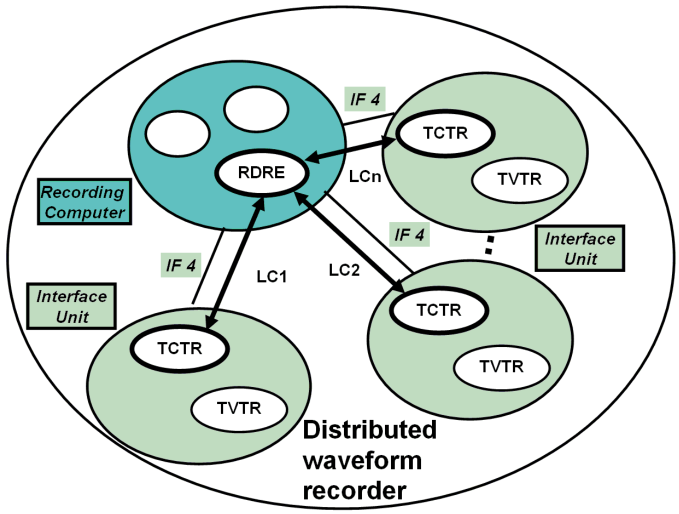

Figure 10: Distributed waveform recorder definition in IEC 61850

The exchange of data is not only between functional elements, but also between different levels of the substation functional hierarchy. It should be kept in mind that functions at different levels of the functional hierarchy can be located in the same physical device, and at the same time different physical devices can be exchanging data at the same functional level.

As can be seen from Figure 10, Logical Connection (LC) is the communications link between functional elements of a distributed waveform recording function - in this case logical nodes of the T and R groups. IEC 61850 also defines the interfaces that may use dedicated or shared physical connections - the communications link between the physical devices.

The allocation of functions between different physical devices defines the requirements for the physical interfaces, and in some cases may be implemented into more than one physical LANs.

IEC 61850 defines functions of a substation automation system (SAS) related to the protection, control, monitoring and recording of the equipment in the substation. These functions can be executed within a single physical device - for example a protection IED - or can be distributed between multiple devices using communications interfaces in the digital substation.

The functions in the substation can be distributed between IEDs on the same, or on different levels of the substation functional hierarchy.

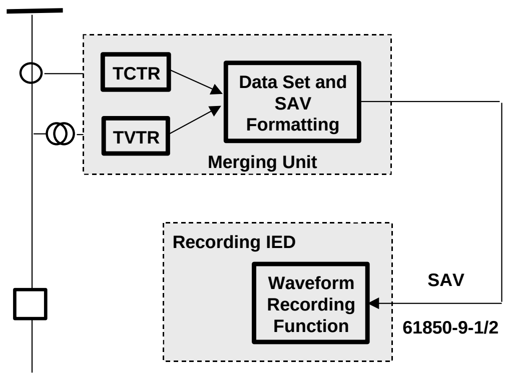

Figure 11: Waveform recording based on Sampled Analog Values

As described earlier, the information exchange for sampled values is based on a publisher/subscriber mechanism.The currents and voltages from **TCTR** and **TVTR** accordingly are delivered as sampled values over the substation LAN using one of the communication modes described earlier in the paper. In this case the network becomes the data bus that provides the interface between the instrument transformer logical nodes and the different logical nodes that are used to model the functional elements of the IED.

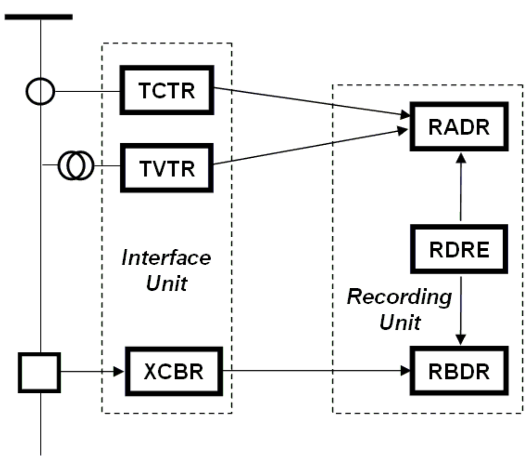

Figure 12: Logical Nodes for waveform recording

The status of the breakers in the substation is modeled using the **XCBR** logical node. It will provide information on the three phases or single-phase status of the switching device, as well as the normally open or closed auxiliary contacts. Figure 4 shows a simplified block diagram of the logical nodes used to model the different components of the waveform recording function. As can be seen from the figure the TCTR, TVTR and XCBR logical nodes are implemented in the different interface units. This name is used instead of merging units due to the fact that the devices have binary inputs in addition to the analog inputs typically available in merging units.

RDRE is the logical node representing the acquisition functions for voltage and current waveforms from the power process (CTs, VTs), and for position indications of binary inputs. RDRE is used also to define the trigger mode, pre-fault, post-fault etc. attributes of the disturbance recording function.

RBDR is used for the different binary signals used in the recording device and RADR logical nodes represent multiple analog channels recorded.

1 Distributed Waveform Recording System Architecture

The distributed waveform recording system architecture includes three types of devices:

- recording device
- interface device
- synchronization device

The synchronization device (or synchronizer) is used to ensure that the waveform recording system meets the requirements for time-synchronization according to the implementation guidelines in [9]. It sends a 1 pulse per second (1PPS) signal through a RS485 network to all interface devices included in the system. Time-synchronization accuracy better than 1 microsecond is achieved by this solution.

The interface units sample 256 times per cycle the three phase current and voltage inputs, as well as the opto inputs and generates the Ethernet messages that are sent using 100 Mb/s to the recording device. As mentioned earlier, 8 sets of current and voltage samples are grouped in each Ethernet frame. As a result, each interface unit sends 32 messages per cycle to the central recording unit.

Each interface unit is connected to an Ethernet switch that in this case is dedicated to the Process Bus.

The recording device receives from the switch all Ethernet messages from the interface units included in the system. Considering the size of the Ethernet frames a single 100 Mb/sec port of the recording device can handle the traffic from up to seven interface units. Figure 5 shows the architecture of a distributed waveform recording system with 3 interface units.

If the central recording unit needs to record currents and voltages from more than 7 interface units, a second Ethernet port may be used to expand the distributed waveform recording system to a total of up to 14 interface units.

Another alternative solution for more than seven interface units is to use a computer with 1Gb/sec Ethernet port connected to a 1 Gb/sec Ethernet switch with 100 Mb/sec ports connected to the interface units. The architecture in this case will be exactly the same as the one shown in Figure 5.

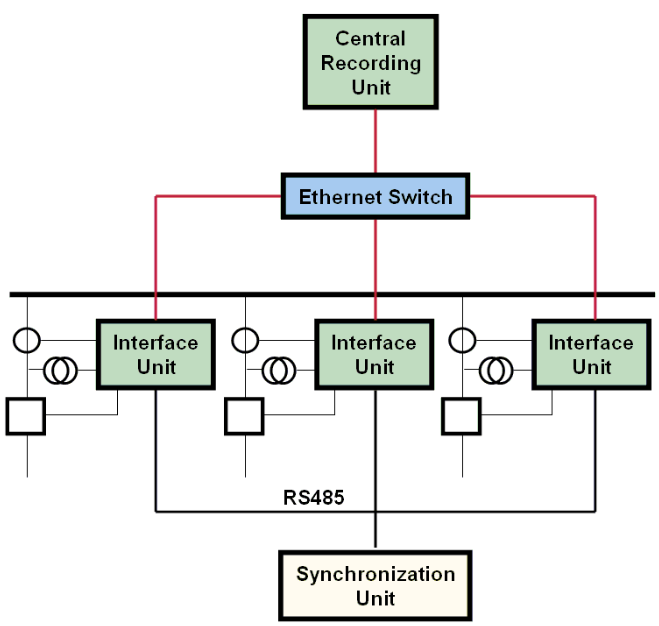

Figure 13: Fig. 5 Waveform recording system architecture

The recording device runs the triggering algorithm, records the samples and generates the COMTRADE files that are stored in its memory for further processing and analysis as necessary.

6. Recording Trigger

The central recording devices receives the Ethernet frames from the multiple interface units and stores them in a buffer so they can be used for detection of a trigger condition or recording when a trigger condition is met.

Two triggering modes can be implemented in the distributed waveform recording system – digital and analog.

Since the interface unit has multiple digital inputs, they can be used not only to monitor the state of breaker auxiliary contacts or electromechanical (or solid state) protection relays, but also to trigger recording of the sampled values.

The digital triggering of recording is the result of any change in the state of a function element, i.e logical node. This is communicated through GOOSE messages and can be based on the start or operate of the logical node.

Recoding can also be triggered based on GOOSE message from an XCBR logical node representing a change of state of a circuit breaker in the digital substation.

Waveform recording, especially with a high sampling rate, can be used for recording not only short circuit fault conditions or other dynamic system parameters variations, but also to capture transient events that might be missed by conventional recording triggers. That is the reason that the analog triggering function can be based on superimposed components of the sampled current a voltage signals.

7. Conclusions

IEC 61850 is a communications standard that allows the development of new approaches for the design of new substations and refurbishment of old ones. A new range of protection and control applications results in significant benefits compared to conventional hard wired solutions.

It supports interoperability between devices from different manufacturers in the substation which is required in order to improve the efficiency of microprocessor based relays applications and implement new distributed functions.

Sampled Analog Values from multiple process interface units are multicast and used by a central recording unit for waveform or disturbance recording in digital substations.

Time synchronization accuracy better than 1 microsecond is achieved using the Precision Time Protocol (PTP) profile for utility applications defined in IEC 61850 9-3.

The central unit performs the triggering and recording, as well as creates waveform records in the COMTRADE file format, using also standard file names.

8. References

[1] INTERNATIONAL STANDARD IEC 61850-9-1, Communication networks and systems in substations – Part 9-1: Specific Communication System Mapping (SCSM) – Sampled values over serial unidirectional multidrop point-to-point link, First edition 2003-05

[2] INTERNATIONAL STANDARD IEC 61850-9-2, Communication networks and systems in substations – Part 9-2: Specific Communication System Mapping (SCSM) – Sampled values over ISO/IEC 8802-3, First edition 2003-05

[3] IEC 61850-9-2 LE: Implementation Guideline for Digital Interface to Instrument Transformers Using IEC 61850-9-2, UCA International Users Group

[4] IEC 61850 9-3 Time Protocol Profile for Power Utility Automation