Disturbance Recording Systems in IEC 61850 Based Digital Substations – Components and Architectures

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Introduction

IEC 61850 based digital substations are the preferred solution for upgraded and new installations due to the improvements in the functionality and efficiency of the system.

Disturbance recording in digital substations is one of the functions that brings significant benefits, but at the same time imposes some challenges that need to be considered during the engineering of the digital substations.

The first part of the paper describes the different components of the disturbance recording system that perform the digitization, measurements, triggering, time synchronization, communications and recording.

The second part of the paper analyzes the impact of the digital substation architecture and the disturbance recording philosophy used. The following systems are described:

- Distributed disturbance recording at the bay or voltage level with local disturbance records generation
- Distributed disturbance recording at the bay or voltage level with local and centralized disturbance records generation
- Centralized disturbance recording system with a single recording data storage

The paper then analyzes the communication architectures that can be used in digital substations and the state-of-the-art redundant solutions based on PRP and HSR.

The impact of the transition to IEC 61869-9 on the disturbance recording systems is described at the end of the paper.

Components of the disturbance recording system

A disturbance recording system in a digital substation has multiple components that perform different tasks and they are connected over the substation communications network according to the design principles implemented.

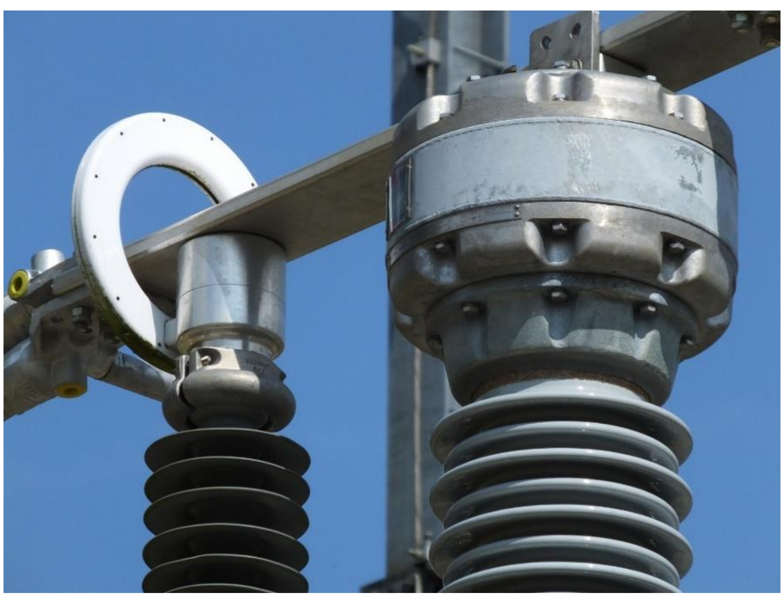

Fig. 1 Optical CT in a digital substation

The first task that needs to be performed is the digitization of the primary current and voltage signals that need to be used to perform the disturbance recording functions.

In substations with traditional instrument transformers the digitization is performed using what is called standalone merging units (SMU) that are connected to the secondary of the current and voltage transformers. They produce a stream of sampled values based on the definitions of the IEC 61850 standard.

In the last couple of decades what is called low powered instrument transformers (LPIT) are being considered as the source of sampled values based on the conversion of the optical signal from an optical CT(Figure 1) or low level voltage signal from a Rogowski coil. The digitization is performed by specialized merging units that can be embedded with the sensor.

Once the analog signals are digitized the published sampled values can be directly used for transient recording by the subscribing devices or further processed to calculate the phasors or synchrophasors of the currents and voltages that can be used for the recording of wide area disturbances.

The triggering of the recording is typically done by a signal from a multifunctional protection IED that has operated during a short circuit fault condition. In the digital substation it is published as a GOOSE message that the disturbance recording element subscribes to.

Fig. 2 Multifunctional IEDs in a digital substation

To perform correct analysis of the different events that are being recorded by the system it is necessary that all components are accurately time synchronized based on the definitions of the precision time protocol (PTP) in the IEEE 1588 standard for time synchronization and its power utility profiles such as IEC 61850-9-3.

Communications are one of the key components of any digital substation based on the Ethernet protocol. Considering their importance, they have to be designed keeping in mind not only the requirements of the protection, automation and control system but also the impact of the disturbance recording functions on the traffic over the network, especially when extracting large disturbance record files.

These files are produced by the disturbance recording functions that may be located in different devices depending on their capabilities and the disturbance recording system architecture.

Impact of the digital substation architecture on disturbance recording systems

The disturbance recording functions can be implemented at all levels of the substation protection automation and control system hierarchy. It can be in the process interface devices, in the different multifunctional IEDs or at the substation level. Regardless of where it is implemented within the digital substation it uses the same object modeling principles based on specific logical nodes defined in the IEC 61850-7-4 standard.

Figure 3 shows a simplified block diagram of the logical nodes used to model the different components of the waveform recording function. **Pxxx** is used to indicate any protection functional element whose status is recorded in the disturbance record. **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. Calculated values such as frequency, power and calculated binary signals may also be recorded by this function if applicable. RDRE is used also to define the trigger mode, pre-fault, post-fault etc. attributes of the disturbance recording function.

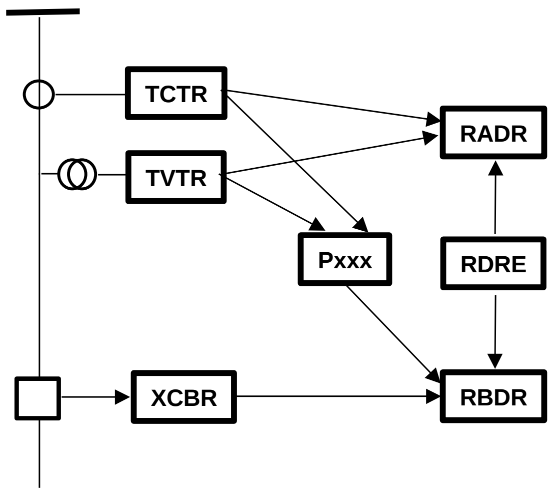

Fig. 3 Logical Nodes for disturbance recording functions

The logical node class **RADR** is used to represent a single analog channel, while **RBDR** is used for the binary channels. Thus, the disturbance recording function is modeled as a logical device with as many instances of RADR and RBDR logical nodes as analog and binary channels are available. The sampled values from TCTR and TVTR are directly used as analog signals by the waveform recording function.

Any disturbance recording device has to be configured to perform this function. The available configuration parameters in a specific device are mapped to the mandatory or optional data objects in the different disturbance recording related logical nodes described above.

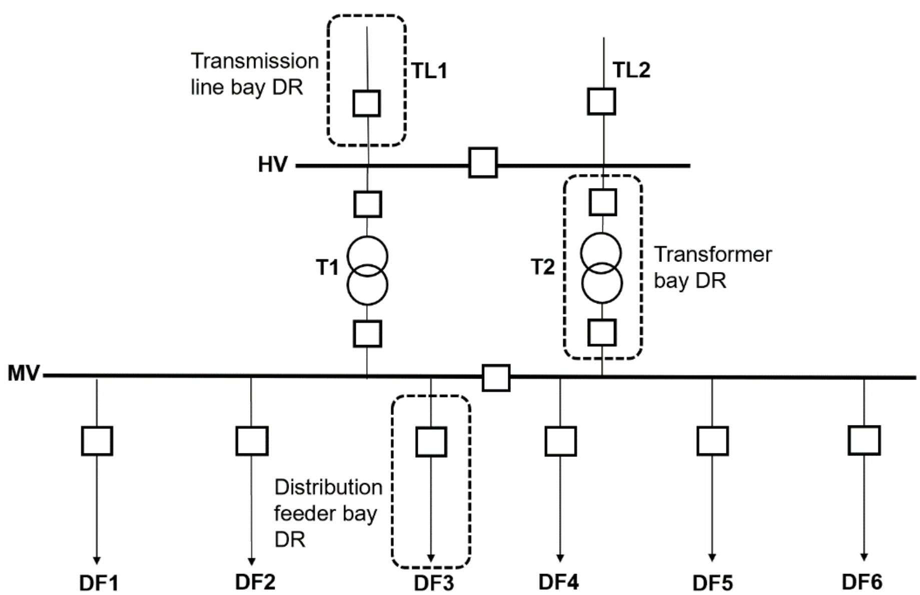

Fig. 4 Bay level disturbance recording architecture

The digital substation architecture and the disturbance recording philosophy used have a significant impact on the traffic over the substation communications local area network. If the disturbance recording function is implemented within the individual multifunctional IEDs there is no traffic over the network until a specific record is required for the analysis of the performance of the PAC system for a specific event. The triggering of the recording is internal to the IED and does not require the publishing of any GOOSE messages for this purpose.

When the disturbance recording is implemented at the Bay level as shown in Figure 4, the traffic is limited only on the segments of the communications network that belong to the Bay that was involved in clearing of a fault or other substation event. The triggering of the recording is internal to the bay and requires the publishing of a GOOSE message from the IED that detected the fault for this purpose. The sampled values (SV) and synchrophasor (SP) communications between the process interface device (Figure 5) and the disturbance recording device are also limited to the network segment belonging to the Bay.

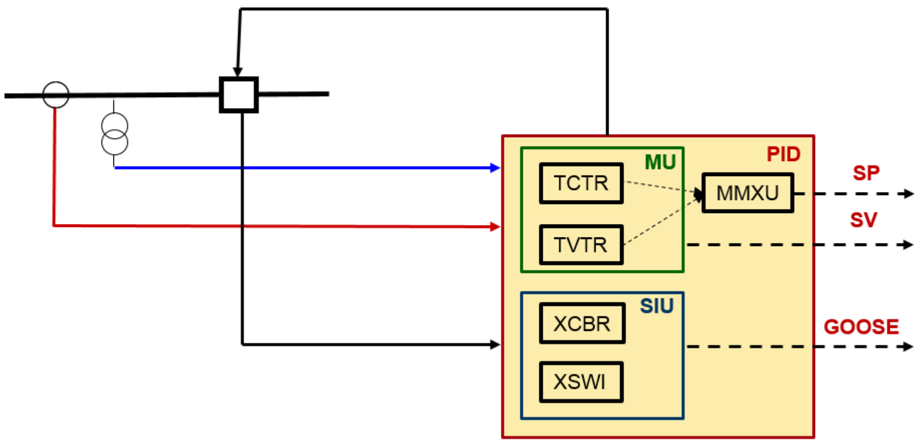

Fig. 5 Process Interface Device

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 may also be used to communicate with a centralized disturbance recording system at the substation level. It can be a standalone device as shown in Figure 6, or an embedded disturbance recording function within the centralized substation protection, automation and control server.

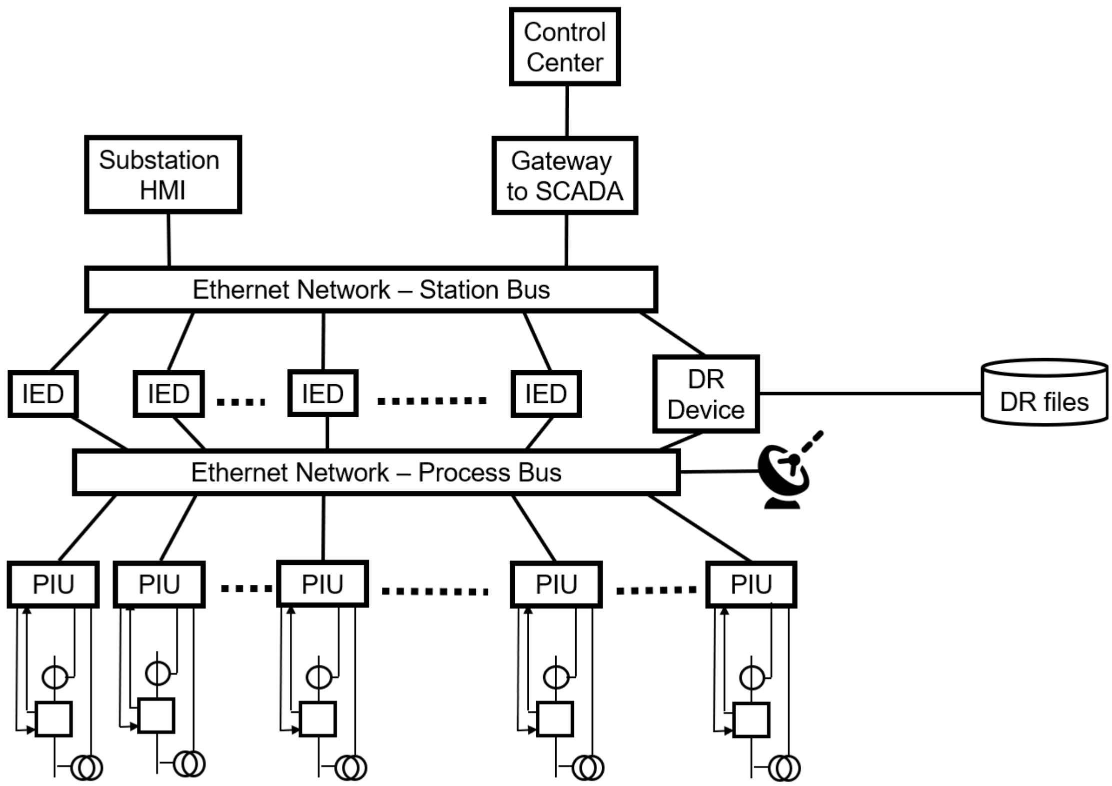

Fig. 6 Disturbance recording system in IEC 61850 based digital substations

When the disturbance recording is implemented like this the traffic for both triggering and recording of short circuit faults or other electric power system disturbances uses all the segments of the substation communications network. The triggering of the recording is distributed and requires the publishing of a GOOSE message from the IED that detected the fault for this purpose.

Communication architectures and time synchronization

Digital substations rely on robust communication protocols to ensure efficient operation and protection. Two key technologies that play a crucial role in this communication are Parallel Redundancy Protocol (PRP) and High-speed Seamless Redundancy (HSR) protocol. These protocols guarantee reliable data transmission even in the face of network failures, making them essential for disturbance recording systems.

The Parallel Redundancy Protocol (PRP) operates on the principle of redundancy. It duplicates all data packets and transmits them simultaneously over two independent communication paths. This creates a fault-tolerant network where a failure in one path wouldn't interrupt the data flow. The receiving device disregards duplicate packets, ensuring seamless data delivery. By eliminating single points of failure, PRP ensures uninterrupted data transfer during disturbances. This is critical for capturing accurate pre-fault, fault, and post-fault data for analysis. Redundant paths also allow for faster detection of network issues. This minimizes the time it takes to initiate corrective actions, potentially reducing equipment damage and downtime.

PRP removes the need for complex redundancy mechanisms like Hot Standby Routers (HSRs). This simplifies network design and reduces maintenance overhead. However, duplicating data packets doubles the traffic on the network, which can be a concern for bandwidth-constrained systems.

High-speed Seamless Redundancy (HSR) takes a different approach to redundancy. It utilizes a dedicated, high-bandwidth ring network with two counter-rotating data streams. Data packets travel in a specific direction within the ring, with redundant copies circulating in the opposite direction. In case of a break in the ring, the redundant data stream seamlessly takes over, ensuring uninterrupted communication.

HSR can pinpoint the exact location of a network fault within the ring, facilitating faster repair times. However, Implementing a dedicated ring network and specialized HSR-compliant devices can be more expensive compared to PRP. Adding new nodes to an HSR ring can be complex and requires careful planning.

Both PRP and HSR significantly improve the reliability and performance of disturbance recording systems because reliable communications ensures capturing complete and accurate pre-fault, fault, and post-fault data for detailed analysis.

Digital substations rely on precise time synchronization to function effectively. Precise timing allows engineers to analyze the sequence of events during a power system fault. Synchronization ensures the measurements are time-stamped accurately, allowing for proper correlation and analysis of grid behavior.

Global Positioning System (GPS) satellites provide a highly accurate time reference. Substation devices can receive GPS signals and synchronize their internal clocks accordingly.

Precision Time Protocol (PTP) is an industry standard that leverages existing Ethernet networks to distribute a synchronized time reference. PTP offers microsecond-level accuracy, making it ideal for digital substations and disturbance recording applications.

Impact of the transition to IEC 61869-9

Most of the digital substations that exists today around the world are using for the communications of the sampled values the IEC 61850 9-2 LE profile. However the trend is that in the future it will be replaced by IEC 61869-9: Instrument Transformers - Part 9: Digital interface for instrument transformers developed by IEC TC38 and published in 2016.

IEC 61869-9 is very similar to IEC 61850-9-2 LE and in order to support interoperability with the large base of existing digital substations devices that are implementing it, it can be configured to be backward compatible. However, it is critical to remember 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.

Another significant difference is in the number of ASDUs per APDU. While in IEC 61850-9-2 LE for protection applications we have 1 ASDU per message and 8 ASDUs per message for disturbance recording related applications. In the case of IEC 61869-9 for protection applications we have 2 ASDUs per message and for disturbance recording 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.

Conclusions

The transition of the electric power industry from hardwired to digital substations brings significant benefits that improve the reliability, security and efficiency of its operations. The digitization of the analog signals based on sampled values communications defined in the IEC 61850 standard plays an important role in this and has an impact on the implementation of disturbance recording functions.

It allows the disturbance recording to be performed at each level of the substation protection, automation and control system hierarchy - starting from the process interface devices, and going to multifunctional IEDs, at the Bay or voltage level, as well as in centralized implementations.

The requirements for disturbance recording need to be taken into consideration during the design of the digital substations and the selection of the redundancy communications protocols such as PRP and HSR, as well as the time synchronization of all devices participating in the disturbance recording system implementation.

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.

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