2008 Georgia Tech Fault and Disturbance Analysis Conference

IMPACT OF IEC 61850 ON FAULT AND DISTURBANCE ANALYSIS SYSTEMS

Alexander Apostolov, OMICRON electronics, USA

I. INTRODUCTION

IEC 61850 is a new approved international standard for substation communications that already has a significant impact on the development of different devices or systems used in the substation. All major substation protection and control equipment manufacturers have products that implement different forms of IEC 61850 communications to simplify integration in substation automation systems and improve the functionality of the system while at the same time reduce the overall system cost. At the same time new solutions are being developed in order to take full advantage of the functionality defined in the standard.

Another important element of IEC 61850 is the object models of all typical functions in a substation automation system. The paper analyses the components of the object model and focuses on the specific Logical Nodes and data objects related to the disturbance recording functions. The distribution of these logical nodes between the different devices in the waveform recording system is discussed later in the paper.

Recording of different abnormal system conditions is very important for their analysis and the identification of methods for improvement in the stability of the electric power system. The design of a good disturbance recording system needs to follow several main steps:

- Take into consideration all the requirements based on the types of events to be recorded by the system
- Determine the recording capabilities of the IEDs existing in the substation
- Analyze the recording capabilities of the IEDs available on the market and select the ones to be used
- Consider the impact of IEC 61850 on the development of new technology that can be used for power system events recording
- Define the optimal fault and disturbance recording and analysis system architecture

These four issues are discussed in more detail in the following sections of the paper.

II. RECORDING REQUIREMENTS

The use of different types of records for analysis of power system events defines the requirements for recording of such events in distribution substations.

Recording of voltage dips and swells imposes quite different requirements from the recording of transients. Even when we think about the recording of voltage variation events, the requirements for an instantaneous are different than for the temporary. Some examples are the non-sinusoidal

---

A. P. Apostolov is with OMICRON electronics, Los Angeles, CA, USA (alex.apostolov@omicronusa.com).

waveforms resulting from switching transients or the voltage and frequency magnitude profiles during a wide area disturbance. As can be seen from these examples, the recording requirements can vary significantly and cover a wide range from more than a hundred samples per cycle of the phase voltages to one sample of minimum, maximum and average values per multiple cycles.

A. Waveform Recording

Waveform recording is available in many power system monitoring devices. 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.

The trigger for waveform recording can be defined as a threshold on any measurement, operation of a protection or monitoring function as well as the output of a user defined programmable scheme logic. External triggering of the recording should also be possible through the opto-inputs of the device or based on communication messages from other IEDs or the substation computer.

B. High- and Low-Speed Disturbance Recording

High-speed or low-speed disturbance recording is intended for capturing events such as voltage sags or voltage swells during short circuit faults on the transmission or distribution system or frequency and voltage variations during wide area system disturbances. The disturbance recording IED stores the values of a user-defined set of parameters for every log interval. 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.

An option to trigger High-speed disturbance recording when a Waveform capture is triggered is achieved by using the same trigger with different recording modes. The combination of waveform capture and high- or low-speed disturbance recording triggered by the same power system event allows the recording of long events, while at the same time providing the details of the transitions from one state to another via the waveform capture. This allows the use of the same event record for the analysis of relay operation or verification of the system models used by different analysis tools.

C. Periodic Measurement Logging

Planning studies and short and long-term load forecasting require the recording of system parameters over long periods of time. The recording device should be able to store the values of a user-defined set of parameters for every log interval. This interval defines the sampling rate of a trend recording and the user should be able to change it as required by the application.

All records – waveforms, disturbances or trends - should be in a standard file format, such as COMTRADE. This allows the use of off-the-shelf programs for viewing and analysis of the records.

III. DISTRIBUTED FUNCTIONS DEFINITIONS IN IEC 61850

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".

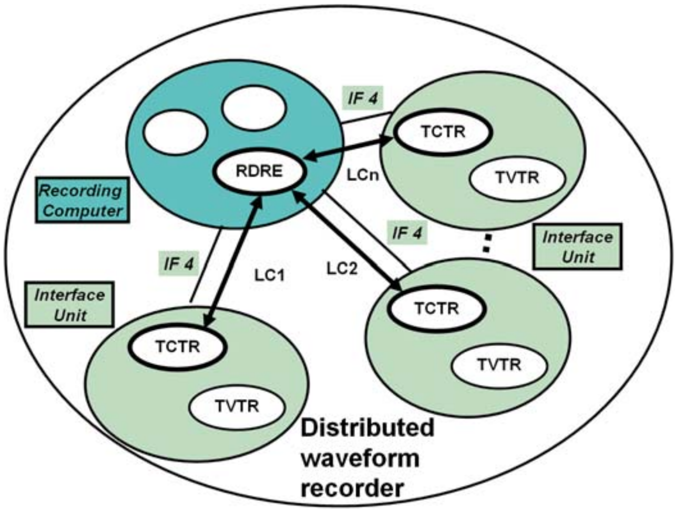

Fig. 1 Distributed waveform recorder definition in IEC 61850

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 1, 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 hard wired or communications interface.

The functions in the substation can be distributed between IEDs on the same, or on different levels of the substation functional hierarchy. These levels and the logical interfaces are shown by the logical interpretation of Figure 2. The distributed recording system can be implemented as a bay level or substation level function. It uses Logical Interfaces 4 from Figure 2.

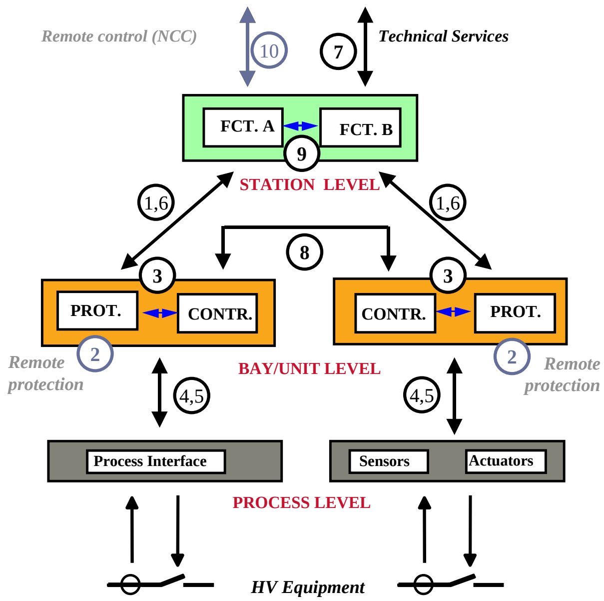

Fig. 2 Logical interfaces in Substation Automation Systems

This interface is defined as follows in IEC 61850:

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

The Process Bus is defined in Part 9 of the standard. In order to better understand the distributed functions as they are defined in an IEC 61850 based system, we need first to clarify the meaning of some of the terms used in the logical interfaces list above.

Perhaps the most important advancement in Ethernet networks is the use of switched Ethernet. Switched networks replace the shared medium of legacy Ethernet with a dedicated segment for each IED. These segments connect to a switch, which acts much like an Ethernet bridge, but can connect many of these single segments. Some switches today can support hundreds of dedicated segments. Since the only devices on the segments are the switch and the end device, the switch picks up every transmission before it reaches another node. The switch then forwards the frame over the appropriate segment, and since any segment contains only a single node, the frame reaches only the intended recipient, thus allowing many conversations to occur simultaneously on a switched network.

Ethernet switching gave rise to another advancement - full-duplex Ethernet. Full-duplex is a data communications term that refers to the ability to send and receive data at the same time. Legacy Ethernet is half-duplex, meaning information can move in only one direction at a time. In a totally switched network, nodes only communicate with the switch and never directly with each other. Switched networks also employ either twisted pair or fiber optic cabling, both of which use separate conductors for sending and receiving data. In the substation environment fiber is the preferred option.

In switched Ethernet the devices connected to the network can forgo the collision detection process and transmit at will, since they are the only potential devices that can access the medium. The end stations in this case can transmit to the switch at the same time that the switch transmits to them, achieving a collision-free environment. That allows the development of new functionality in substation automation systems practically impossible in the hub based LAN at the early stages of the development of UCA 2.0 GOMSFE. The performance of protection and other distributed functions is further improved through the availability of priority tagging defined as Virtual LAN (VLAN). VLAN is a group of devices on one or more LANs that are configured in such a way that they can communicate as if they were attached to the same wire, when in fact they are located on a number of different LAN segments. The IEEE 802.1Q specification establishes a standard method for tagging Ethernet frames with VLAN membership information. The key for the IEEE 802.1Q to perform the above functions is in its tags. 802.1Q-compliant switch ports can be configured to transmit tagged or untagged frames. A tag field containing VLAN (and/or 802.1p priority) information can be inserted into an Ethernet frame. If a port has an 802.1Q-compliant device attached (such as another switch), these tagged frames can carry VLAN membership information between switches, thus letting a VLAN span multiple switches.

The tagged Ethernet frame is shown in Table 1 below and can help us understand how the different communication modes work in the Ethernet network environment.

Table 1 Ethernet frame

Pre	SFD	DA	SA	Priority Tagged	ET	Length Type	MAC Data + Pad	FCS
7	1	6	6	4	2	2	42-1496 bytes	4

Where:

Pre: The Preamble is an alternating pattern (7 bytes) of ones and zeros that tells receiving stations that a frame is coming and provides a means to synchronize the frame-reception portions of receiving physical layers with the incoming bit stream.

SFD: Start-of-frame delimiter (1 byte: 10101011) indicating that the next bit is the left-most bit in the left-most byte of the destination address.

DA: Destination address (6 bytes) identifies which station(s) should receive the frame

SA: Source addresses (6 bytes) identifies the sending station

Priority Tagged (Virtual LAN) includes:

- TPID – 2 byte Priority Tagging Identification (for IEEE 802.1Q Virtual Bridged Local Area Networks)
- TCI – 2 byte Tagged Control Information

ET: Ethertype - A 2 byte code indicating protocol type in an Ethernet packet. The Ethertypes for IEC 61850 are shown in Table 2.

Table 2 IEC 61850 Ethertypes

Assigned Ethertype values

Use	Ethertype value (hexadecimal)	APPID type
IEC 61850-8-1 GOOSE	88-B8	0 0
IEC 61850-8-1 GSE Management	88-B9	0 0
IEC 61850-9-2 Sampled Values	88-BA	0 1

Length Type: Indicates either the number of MAC-client data bytes that are contained in the data field of the frame, or the frame type ID if the frame is assembled using an optional format

MAC Client Data: A sequence of *n* bytes (42=< n =<1496) of any value. (The total frame minimum is 64 bytes). The Pad contains (if necessary) extra data bytes in order to bring the frame length up to its minimum size. A minimum Ethernet frame size is 64 bytes from the Destination MAC Address field through the Frame Check Sequence.

FCS: The Frame Check Sequence is a 32-bit cyclic redundancy check (CRC) value, which is created by the sending MAC and is recalculated by the receiving MAC to check for damaged frames

The IEC 61850 based process bus solutions use different communication modes supported by Ethernet. This is achieved by using a different Destination Address (DA in Table 1).

Unicast communication takes place over the network between a single sending IED and a single receiving IED. The Destination Address identifies a unique device that will receive the Ethernet frame.

Multicast is the addressing mode in which a given frame is targeted to a group of logically related IEDs. In this case the Destination Address is the Multicast Address, also called a "group" address. This mode is used in the distributed waveform recording system described in the paper.

IV. WAVEFORM RECORDING BASED ON SAMPLED ANALOG VALUES

The introduction and wide spread of microprocessor based protection devices, combined with the advancements in non-conventional instrument transformers resulted in the development of digital interface between the sensors and the IEDs.

Digital interface in a point-to-point communications scheme was defined by IEC in the IEC 60044-8 standard. The development of Merging Units that convert the optical signal into a digital message containing sampled values and protection devices with a digital interface that perform multiple protection functions resulted in demonstration projects that show the advantages of this technology.

IEC 61850 further developed the sampled analog values interface at the process level of the substation automation system. This is the logical interface 4 shown in Figure 2 between the process and the bay levels.

The frame format from IEC 60044-8 is reused, but the new standard defines the transmission of sampled analog values over the Ethernet in both a point-to-point (unicast) or multicast mode.

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. 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.

The transmission of sampled values requires special attention with regard to the time constraints. The model provides transmission of sampled values in an organized and time controlled way so that the combined jitter of sampling and transmission is minimized to a degree that an unambiguous allocation of the samples, times, and sequence is provided.

The sampled analog values model applies to the exchange of values of a DATA-SET. 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 instrument transformer logical nodes TCTR and TVTR (Figure 3).

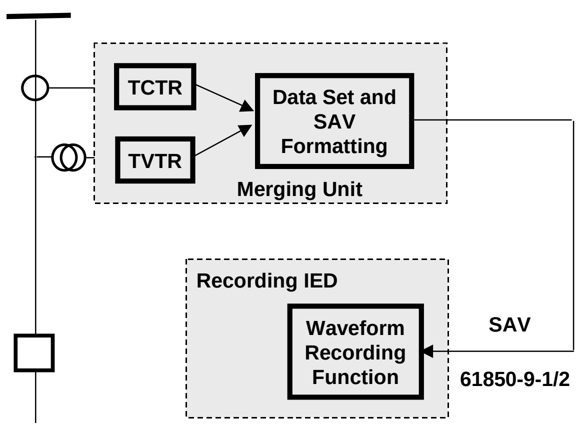

Fig. 3 Waveform recording based on Sampled Analog Values

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 3), 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 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.

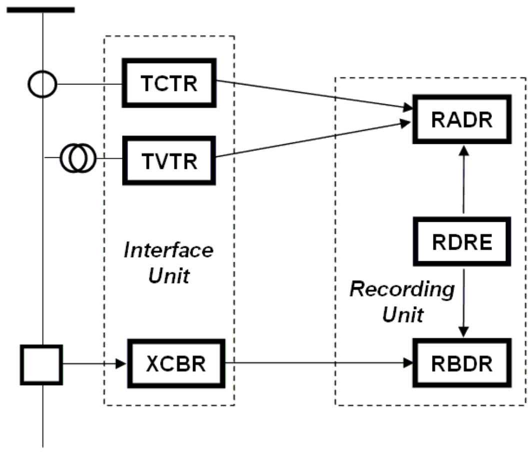

Fig. 4 Logical Nodes for waveform recording

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.

V. 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. 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.

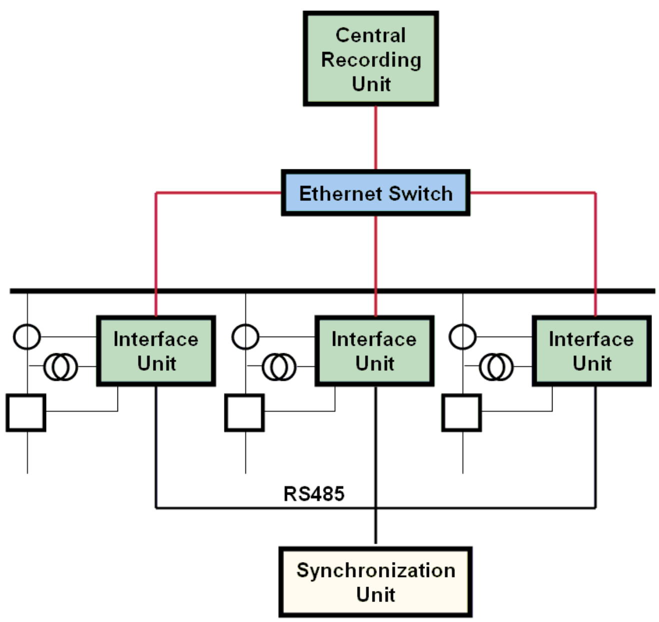

Fig. 5 Waveform recording system architecture

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.

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 are implemented in the distributed waveform recording system – digital and analog.

Digital triggering

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 digital input as a function of its setting. The recording can be triggered in case of one of the following three options:

- rising edge
- falling edge
- both

To avoid the effect of contact jitter on the detection of change of state of a binary input, two main methods are implemented – one in the interface unit and the other in the central recording unit.

A decision that a change of state of a digital input of the interface unit has occurred is made after the input has had the same state for 10 consecutive samples (considering that the sampling rate is 256 samples/cycle).

The digital recording triggering in the central unit is based on checking the state of a digital signal 16 times per cycle, i.e. about every millisecond in a 60 Hz system. The time stamping of the digital input change of state is then based on the first of the previous 15 samples that had the new detected state change. The accuracy of the time stamp is in microseconds.

Analog Triggering

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 is based on superimposed components of the sampled current a voltage signals.

When a fault, such as a short circuit, occurs in the electric power system, it leads to a dynamic transition from the normal system condition to a fault system condition. The currents and voltages measured by the device will change as a function of the pre-fault system configuration, as well as the parameters of the fault - fault type, fault location, fault resistance, etc.. In this case the faulted network state can be considered as the result of the superposition of the pre-fault and the fault generated quantities:

$$\Delta UA = UA_f - UA_{pf} \qquad (1)$$

$$\Delta IA = IA_f - IA_{pf} \qquad (2)$$

where:

IA_{pf} pre-fault current at relay location

UA_{pf} - pre-fault voltage at relay location

IA_{f} - fault current at relay location

UA_{f} - fault voltage at relay location

ΔIA - fault generated current at relay location

ΔUA - fault generated voltage at relay location

The use of superimposed components in the central unit for recording triggering provides numerous benefits based on the fact that it is directly related to the transient system conditions.

The calculation of the superimposed components of the phase currents and voltages is based on the latest samples measured and samples stored in the memory of the device (see Figure 5). There are different approaches to the derivation of the superimposed components.

The general aim is to estimate what the expected no-fault current or voltage sample should be at this moment and then subtract that from the latest sample captured.

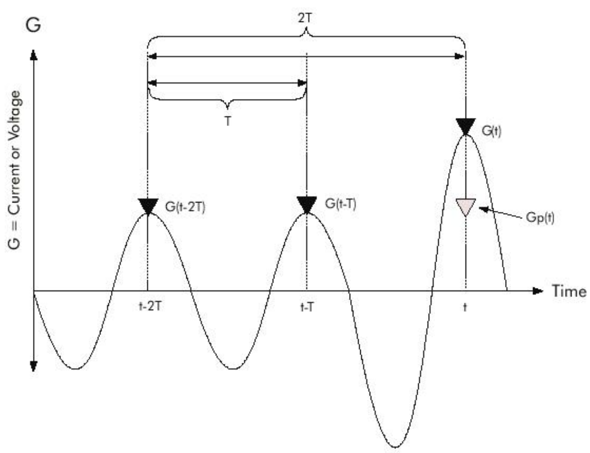

Fig. 6. Superimposed components calculation

The method used is based on two samples from the buffered samples, captured one and two cycles earlier than the last sample captured by the relay at the same angle on the wave form to predict the expected non-fault sample value at time (t). The size of this buffer is a function of the sampling rate of the recording system and the configured pre-trigger recording time. It also is a function of the number of interface units used in the system.

The superimposed components of the different parameters $\Delta G(t)$ are calculated as follows:

$$Gp(t) = G(t-T)+(G(t-T)- G(t-2T)) \qquad (3)$$

$$Gp(t) = 2.G(t-T) - G(t-2T) \qquad (4)$$

$$\Delta G(t) = G(t)- Gp(t) \qquad (5)$$

where

G(t) current or voltage sample at time (t)

G(t-T) current or voltage sample one cycle prior to (t)

G(t-2T) current or voltage sample two cycles prior to (t)

Gp(t) predicted value at time(t)

ΔG(t) superimposed component of current or voltage at (t)

An advantage of the above method for calculation is that it provides a good estimate of the predicted sample value based on two pre-fault samples. File Naming Convention

The names of the COMTRADE files created by combining the sampled values from the different interface units that are stored in the memory of the central recording unit are based on a new emerging standard – IEEE PC37.232, D4.5 Draft Recommended Practice for Naming Time Sequence Data (TSD) Files [10].

This filename was selected because it is human readable and includes, among other features, key portions of the information contained in the file including, but not limited to, the name of the circuit, substation and recording device, and the date and time of initial occurrence. It allows the development of search functions that can be used for different fault analysis tasks.

VI. DISTURBANCE RECORDING BASED ON IEC GOOSE MESSAGES

These applications can be considered as a transition between the distributed applications based on status change information in GSSE messages and the applications based on sampled analog values.

Figure 7 shows simplified block diagram of the disturbance recording function based on IEC GOOSE.

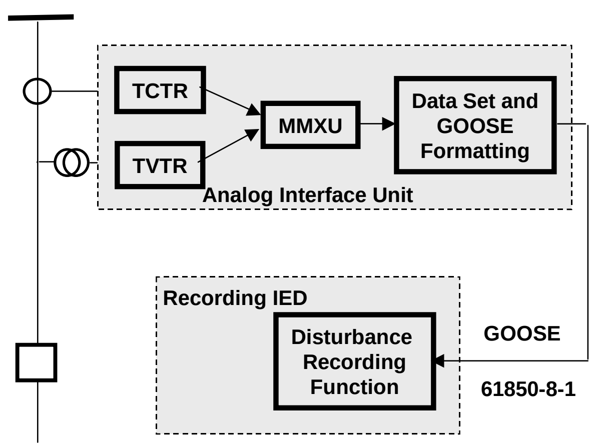

Fig. 7 Disturbance recording based on IEC GOOSE

As described earlier, the input transformer logical nodes convert the analog signals to sampled values and send them over the IED data bus to the main processing module. The MMXU is the logical node that represents a function in the IED that calculates from the sampled values different system parameters, such as the frequency or voltage.

The logical nodes involved in the distributed disturbance recording function are shown in Figure 8.

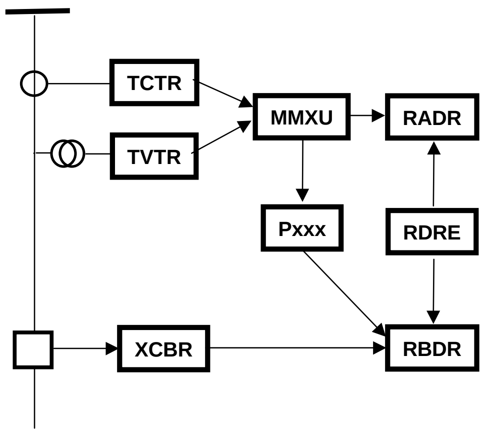

Fig. 8 Logical nodes for disturbance recording

The same approach can also be used for recording of load trends. The difference in this case will be in the recorded system parameters, as well as the sampling rate that will be in the range of minutes, compared to the cycles used for the disturbance recording.

VII. ANALYSIS OF IED OPERATION

The analysis of protective relays operation is based on the different reporting functions in these IEDs, such as Event reports, Fault records and Waveform records. In many cases the fault records are included in the event report.

Event reports in IEC 61850 are based on Report Control Blocks that control the procedures required for reporting values of event data from one or more logical nodes to one client. Instances of report control are configured in the IED at configuration time.

IEC 61850 defines two classes of report control:.- Buffered Report Control Block (**BRCB**) and Unbuffered Report Control Block (**URCB**).

Buffered Report Control Blocks are used for sequence of event purposes. They define internal events (caused by trigger options data-change, system-change, and data-update) that issue immediate sending of reports or buffer the events for transmission. This prevents from data being lost in case of loss of connection.

Unbuffered Report Control Blocks are quite similar to the **BCRB**. However they don't buffer the data, so event information may be lost in the case of communication problems. Obviously the unbuffered report control block does not support sequence of events reporting in case of loss of communications.

Waveform records are typically saved as a file or set of files (according to the COMTRADE specifications). Retrieval of such files requires file transfer support in the communications protocol. IEC 61850 supports file transfer, so it can be used to support the waveform records extraction function.

VIII. CONCLUSIONS

The new IEC 61850 international standard for substation communications enables the development of different distributed waveform recording systems. It allows a new approach to recording of transients, faults or other abnormal conditions with sampling rate of 256 samples/cycle.

In the case of specialized disturbance recording devices GSSE messages can be used for cross-triggering over the substation LAN.

Sampled Analog Values from Merging Units are multicast or unicast and used for waveform recording.

The IEC GOOSE messages are used to send the measured voltage, frequency or other values for high or low speed disturbance recording or load trends.

Sampled Analog Values from multiple interface units are multicast and used by a central recording unit for waveform recording.

Time synchronization accuracy better than 1 microsecond is achieved using a dedicated synchronizer.

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