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Analysis of Recording Elements in Wide Area Monitoring Systems

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SUMMARY

Recording of different types of power system events is extremely important for the successful analysis of wide are disturbances and the verification of the system models used in the design of protection and emergency control systems. The paper discusses the recording elements in different types of multifunctional Intelligent Electronic Devices. The effect of analog and digital filtering, sampling rate, recording and storage methods on the quality of the records is analyzed in the paper.

Even that the recording of analog values is the primary function of disturbance recording devices, the capture of change of state of monitored binary inputs is also important for the analysis of the operation of substation primary or secondary equipment. Methods for detection and their effect on the accuracy of time-stamping are presented in the paper.

IEC 61850 is the new international standard for communications in substations. It defines station and process bus communications between the different components of the system:

The paper describes the different components of a system for recording of wide area disturbances in substation automation systems with IEC 61850 based communications. The distribution of functions between the individual devices is analyzed from the point of view of system architecture and reliability requirements.

Process interface devices (Merging Units) are described as forming the data acquisition layer in the distributed recording system. They communicate over a 100 Mb/sec Ethernet with a central computer that records the system transient event with 256 samples/cycle.

The paper describes the architecture of the system, recording triggering criteria and the system performance requirements.

Accurate time synchronization is a key requirement for any distributed recording system. The accuracy of time synchronization is another critical attribute of the recording IED. The paper discusses different methods for time-synchronization used today, as well as the emerging IEEE 1588 standard.

KEYWORDS

Wide area monitoring and recording, analysis, multifunctional IEDs

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I. INTRODUCTION

Recording of different types of power system events is extremely important for the successful analysis of wide are disturbances and the verification of the system models used in the design of protection and emergency control systems.

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II. RECORDING REQUIREMENTS

In order to define the requirements for recording of wide area system disturbances, we need to answer two basic questions.

- Why do we need to record wide area disturbances?
- What do we need to record?

The experience from the analysis of the August 14, 2003 blackout significantly helps in answering both of these questions. The first answer is quite obvious - without recordings it would have been completely impossible to reach any conclusions about the cause of the blackout.

Since wide area disturbances include changes in the monitored system parameters that can range from fractions of a cycle to several minutes, it is impossible to record the variety of events using the most commonly available waveform capture. Many of the power system events are also based on the changes in the RMS value of the voltages, so the waveform capture is not appropriate for the recording of such events.

At the same time there are many other power system applications that require the recording of different system parameters with different sampling rates. That is why multifunctional protection and monitoring IEDs provide recording features that can be used to meet the primary and backup recording requirements of various utility departments.

The need for monitoring and recording at the transmission level has been recognized for a long time. The experience with centralized disturbance recording systems has shown how valuable this information is in order to allow for a better understanding of the steady-state and dynamic behavior of the system. The availability of multifunctional IEDs with advanced communications capabilities and a standard communication protocol leads to a new concept for distributed monitoring and recording not only in the substation, but throughout a complete electric power system.

The recording modes of multifunctional IEDs are determined by the requirements for recording of different system events. Wide area system disturbances that result in power swings or frequency variations, transients during a short circuit on a high voltage transmission line or the voltage sag at the distribution level, load changes caused by time of day or meteorological condition variationsimpose recording requirements that can vary significantly and cover a wide range from more than a hundred samples per cycle, to more than a minute between samples, i.e. in some cases sampling of the waveform, while in other a periodic log of the RMS value of the monitored parameter.

It is important to understand the recording capabilities of the IEDs available in a substation automation system. The protection relays typically record waveforms in order to allow post fault analysis of the operation of the relay under the specific fault conditions. The sampling rates of the relays can vary significantly – from 4 samples/cycle in some of the early relays, to 64 or 128 samples/cycle in modern relays. Even that these sampling rates may meet the requirements for protection operation analysis, they may miss some details in the recording of transients due to the analog and digital filters in the analog input processing.

The available memory and recording modes in microprocessor based relays are another issue that needs consideration when selecting the recording devices for wide are disturbances. Even that some relays can record waveforms of events up to 10.5 seconds long, it is clear that they can not be used for recording of events that take longer than that. Also, for analysis of voltage and frequency variations there is a need of further processing of the recorded waveforms to calculate the values of the system parameters of interest.

That is why specialized state-of-the-art multifunctional IEDs with recording capabilities have multiple recording types that allow the coverage of any possible type of fault or power system event. They sample the current and voltage waveforms with high sampling rates and calculate system parameters several times per cycle. This allows the user to select the right recording mode depending on the type of event to be analyzed. In order to allow the user to "zoom-in," all recording modes should run in parallel, as required by the application, power system condition and triggering criteria specified by the user. This is possible, since the same triggers can be used for the different types of recording and also because all records have accurate time stamps based on the time-synchronization feature in the IEDs.

Waveform Recording

Waveform recording in many cases is known as disturbance recording. It captures the individual samples of the currents and voltages measured by the IED with a sampling rate that may be as low as 4 samples/cycle for some low-end protection IEDs to 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 waveform recording trigger 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 should also be possible through the opto inputs of the IED or based on a communication message from another IED.

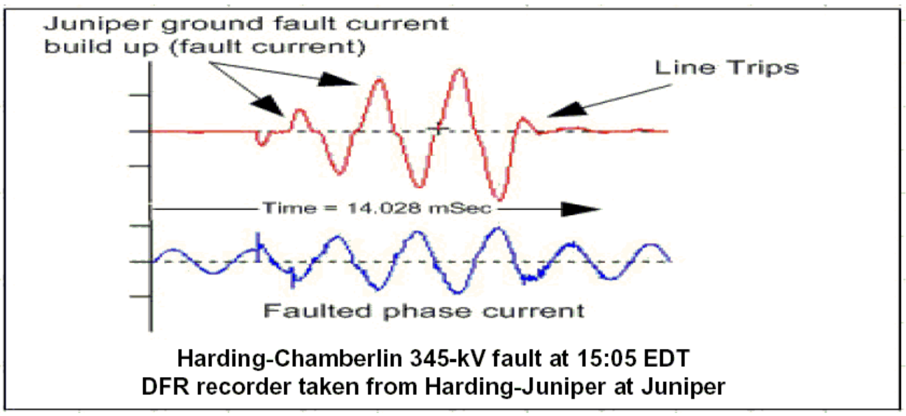

Fig. 1 Waveform record of a 345 kV line fault during the August 2003 blackout [1]

High- and Low-Speed Disturbance Recording

High-speed disturbance recording is intended for capturing high-speed power system events such as power swings following short circuit faults on the transmission system.

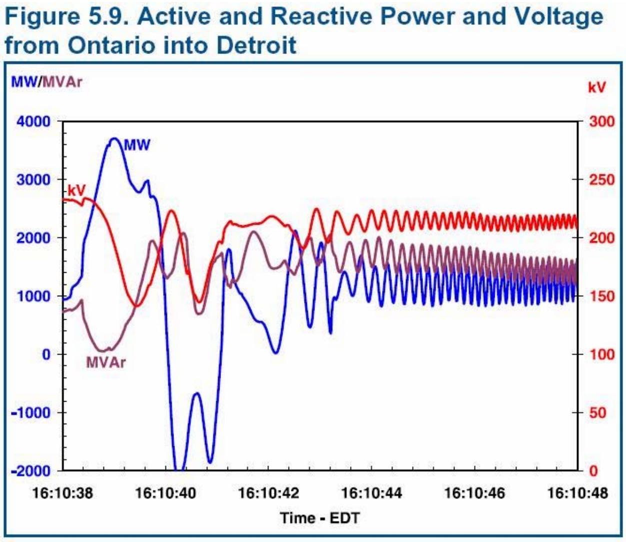

Fig. 2 High-speed disturbance record of power and voltage variations during the August 2003 blackout [1]

Low-speed disturbance recording can be used to capture power system oscillations following generator tripping or other system events, such as in Figure 2.

The disturbance recording IED stores the values of a user-defined set of parameters for every log interval. The setting range should allow the user to define the sampling rate, for example from 1 to 3600 cycles and can be changed with a step of 1 cycle.

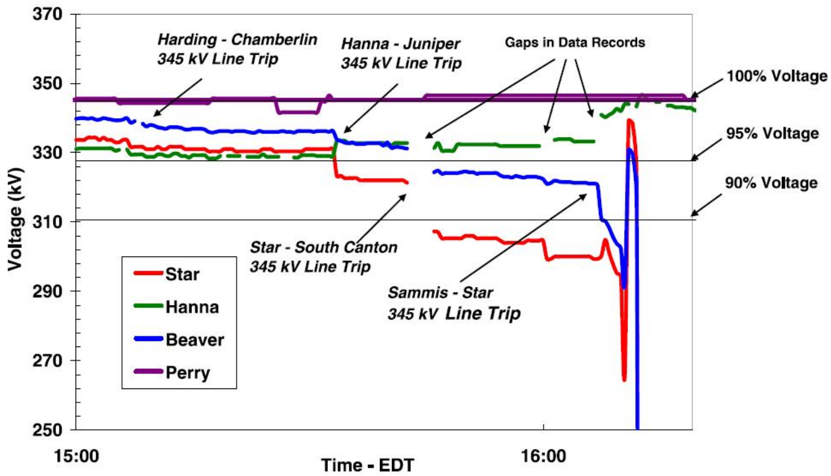

Fig. 3 Low-speed disturbance record of voltage profiles during the August 2003 blackout [1]

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.

The measurement log file can contain user settable number of samples. For example, a record with 3072 samples is equivalent to 32 days of logging when using a sampling interval of 15 minutes. Once the log file has reached its maximum length it will wrap around to the beginning and overwrite the oldest entries in the file. For each parameter the minimum, maximum, and average values that occurred during the previous interval might be required to be recorded.

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. Since this is a comma separated text format, the files can easily be imported in other applications for further processing.

III. DISTRIBUTED RECORDING ARCHITECTURE

Modern multifunctional IEDs with monitoring, control and protection functions are typically being integrated in hierarchical substation protection and control systems.

The installation of advanced multifunctional protection, control, power quality monitoring and recording devices result in a very efficient solution that meets all requirements for primary and backup monitoring and recording in substation automation system.

Because of the high sampling rate and the availability of multiple recording modes, it is obvious that power quality monitoring or specialized disturbance recording devices will be used as the primary recording devices. Multifunctional protection devices will be used as the backup recording devices.

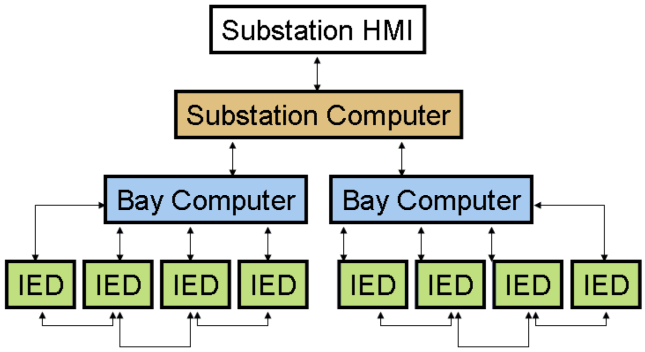

Fig. 4: Simplified substation automation system architecture diagram

The sampling rates of the relays might not be appropriate for some harmonic calculations, but they are still OK considering that they perform backup recording functions only.

The functional architecture of a substation automation system shown in Fig. 4 has a multi-level architecture. All IEDs are connected to a substation local area network (SLAN). They represent the lower level, directly related to the individual power equipment in the substation - transformers, distribution feeders, transmission lines, buses, etc.

Bay computers (or Bay Controllers) perform functions at the second level, such as distributed bus protection based on the directional detection in multifunctional IEDs connected to the transmission or distribution bus controlled by the Bay Computer.

A substation computer is also connected to the SLAN and performs multiple functions based on the data and information available from the IEDs at the power equipment level and the bay computer's level. It represents the substation level in the hierarchy. Typical functions include the Human Machine Interface (HMI), alarm and event logging at the substation level, settings, control, load profiles and analysis, etc. It also includes the centralized power system analysis functions.

The event logs from multiple devices during wide area system disturbances and other power system events can be analyzed at the substation level in order to determine the cause of the event and its effect on different customers that were supplied with power from the substation.

Recording can be performed at each level of the substation functional hierarchy. After the records have been extracted automatically by the analysis system, they can be combined in new records based on the requirements of the applications. Primary and backup recording functions can be distributed between the different IEDs as shown in the table below.

Recording Functions	**Primary**	**Backup**
Waveform recording	PQ Monitoring or Recording IED	Protection IED
Disturbance recording	PQ Monitoring or Recording IED	Substation HMI
Trend recording	PQ Monitoring or Recording IED	Substation HMI

The analysis system also has hierarchical structure which in the case of wide area analysis covers not only the substation, but also regional and system levels. A simplified diagram of a wide area analysis system is shown in Figure 5.

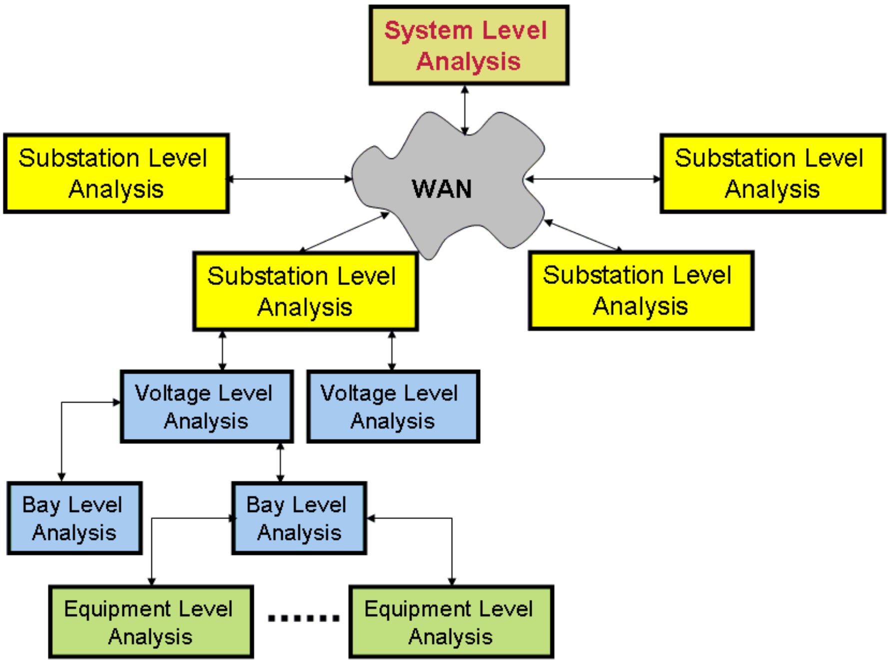

Fig. 5: Wide area analysis system architecture

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.

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 32 times/cycle [2].

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, 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.

The currents and voltages from the merging unit 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.

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 [2]. The requirements for high accuracy time synchronization achieved using a standard method over

Ethernet is becoming very important due to the introduction of high-speed peer-to-peer communications based applications in IEC 61850 substation automation systems. The synchronization for the typical substation automation and control applications in such systems today will be based on SNTP, which provides sufficient accuracy to meet the usual requirement for 1 millisecond time-stamp accuracy. However, for synchrophasor based applications 1 microsecond accuracy is required. It can not be achieved using SNTP. That is why vendor proprietary solutions might be used.

One such solution is uses a synchronizer that 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 problem is that this violates one of the main requirements for IEC 61850 based systems – interoperability. That is why a lot of attention is being paid to the new IEEE 1588 time synchronization standard that defines the Precision Time Protocol (PTP). It allows sub-microsecond synchronization of real-time clocks and is applicable to local area networks supporting multicast communications (including but not limited to Ethernet).It is being considered for time synchronization in future distributed recording systems, including such applications as wide area monitoring and recording.

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 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 6 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 6.

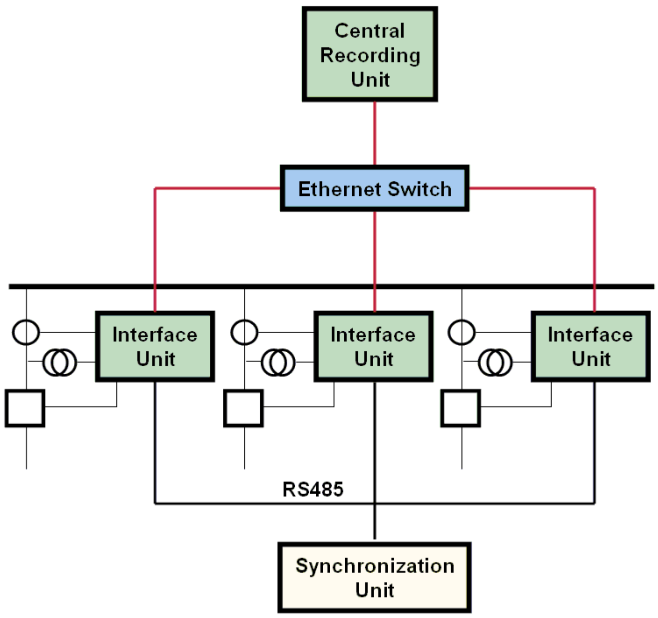

Fig. 6 Waveform recording system architecture

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.

The digital triggering of recording is the result of any change in the state of a digital input as a function of its setting and can be based on rising edge, falling edge or both. Analog triggering can be based on continuous monitoring of the sampled values of the currents and voltages and comparison with user defined thresholds. Superimposed components based triggering offers advantages in both sensitivity and speed.

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 [3].

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 wide area analysis tasks.

V. CONCLUSIONS

The variety of events that lead to a wide area disturbance impose different requirements for their recording. The integration of multifunctional IEDs with protection and monitoring/recording functions in IEC 61850 based substation automation systems allows the implementation of distributed systems for recording of wide area disturbances.

Three different types of records with appropriate sampling rate ranges and record length are identified in the paper:

- Load profiles or trend records
- High- or Low-speed disturbance records
- Waveform capture

The combination of waveform capture and high or low-speed disturbance recording triggered by the same system condition allows the recording of long events, while at the same time the details of the transitions from one state to another are recorded in the waveform capture.

Extended recording memory ensures that no data is lost during wide area disturbances with long duration.

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

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

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

Time synchronization accuracy is a key requirement for the recording of wide area disturbances. It can not be achieved using SNTP. Accuracy better than 1 microsecond is achieved using proprietary methods in a dedicated synchronizer. IEEE 1588 defines the Precision Time Protocol (PTP). It allows sub-microsecond synchronization of real-time clocks and is applicable to local area networks supporting multicast communications (including but not limited to Ethernet).It is being considered for time synchronization in future distributed recording systems, including such applications as wide area monitoring and recording.

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