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Distributed Recording of Abnormal Power System Conditions

Alexander Apostolov, James Butt
ALSTOM T&D Bitronics

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1. Introduction

The electric power utility industry requires significant improvement in the quality of power supply provided to customers and the stability of the power system during faults or wide area system disturbance. This is related to the availability of tools that help energy management, planning and protection engineers to understand the processes in order to optimize the operation of the system under different abnormal conditions.

The paper presents the concept of a system for distributed monitoring and recording of the system behavior. It discusses the functionality of IEDs for monitoring and recording of abnormal systems conditions. Different types of abnormal system conditions at the distribution, sub-transmission and transmission levels of the power system are described at the beginning of the paper. The characteristics of the process and the requirements for their recording for further analysis, as well as the criteria for detection of different types of abnormal conditions are presented later in the paper.

Four different types of records with appropriate sampling rate ranges and record length are identified:

- Load profiles
- Low-speed abnormal system conditions
- High-speed abnormal system conditions
- Waveform capture

The use of each recording type for specific abnormal conditions at the transmission or distribution level of the system is described.

The record data format and the substation local area network (LAN) architecture in order to integrate the IEDs into a substation monitoring and control system are discussed from the perspective a complete system that provides primary and backup recording functionality.

The application of high-speed peer-to-peer communications in a distributed disturbance recording system is presented at the end of the paper.

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.

More and more utilities and industries are realizing that the same is true at the distribution level. The availability of multifunctional IEDs with advanced communications capabilities leads to a new concept for distributed monitoring and recording not only in the substation, but throughout a complete electric power system.

2. Recording Requirements for Transmission Systems

Recording is very important for the analysis of the behavior of the electric power system under normal or abnormal system conditions. That is why each utility develops standards for monitoring of the power system. These standards are to a great extent defined by the requirements of the NERC (North American Electric Reliability Council) Planning Standards. They specify the adequate installation and characteristics of disturbance monitoring equipment that is needed to provide the necessary data to analyze the system performance and to determine the cause of a system disturbance or other abnormal system conditions.

The data available from different types of disturbance recording equipment can be used for the development, maintenance and updating of transmission system models used for load flow or dynamic stability studies.

It is difficult to describe all system events that may require recording of system parameters for their analysis, that is why we will discuss just a few examples that give an idea of the differences in recording requirements.

2.1. Trends

The planning of the power system is based on complex load-flow and dynamic stability studies. They require good steady-state and dynamic models that need periodic verification based on comparison between the calculated and the actual power system parameters.

Continuous recording of the system voltages, currents, active, reactive and apparent power can help planning engineers make decisions on the need for building new transmission lines or generating stations, define the requirements for remedial-action schemes in case of loss of generation or important interconnections.

The recorded information, combined with additional data can be used for short, medium and long-term forecasting.

The recorded information has to be time-stamped with sufficient accuracy in order to allow the data from all recording devices distributed through the system to be synchronized. The sampling rate for all devices should be the same, with typical values in the range from 1 to 15 minutes.

2.2. Low speed-disturbance

The normal system conditions are the result of a balance between load and generation at each moment in time. Any change in this balance will cause changes in some of these parameters that in some severe cases may lead to a local or wide spread system disturbance. One parameter that can be used to monitor and analyze such conditions is the frequency.

The system frequency fluctuates in case of a change in the production or in the demand of energy. When a generator trips, the frequency will decline as a function of the size of the generator and the total load in the system. Depending on the prime mover and spinning reserve, the frequency will eventually go back to its desired value. If the loss of generation is greater than the spinning reserve, the frequency will eventually stabilise to new value lower than the nominal

(Fig. 1). If the frequency decline is excessive, generating units can be automatically tripped off causing an additional decline of frequency.

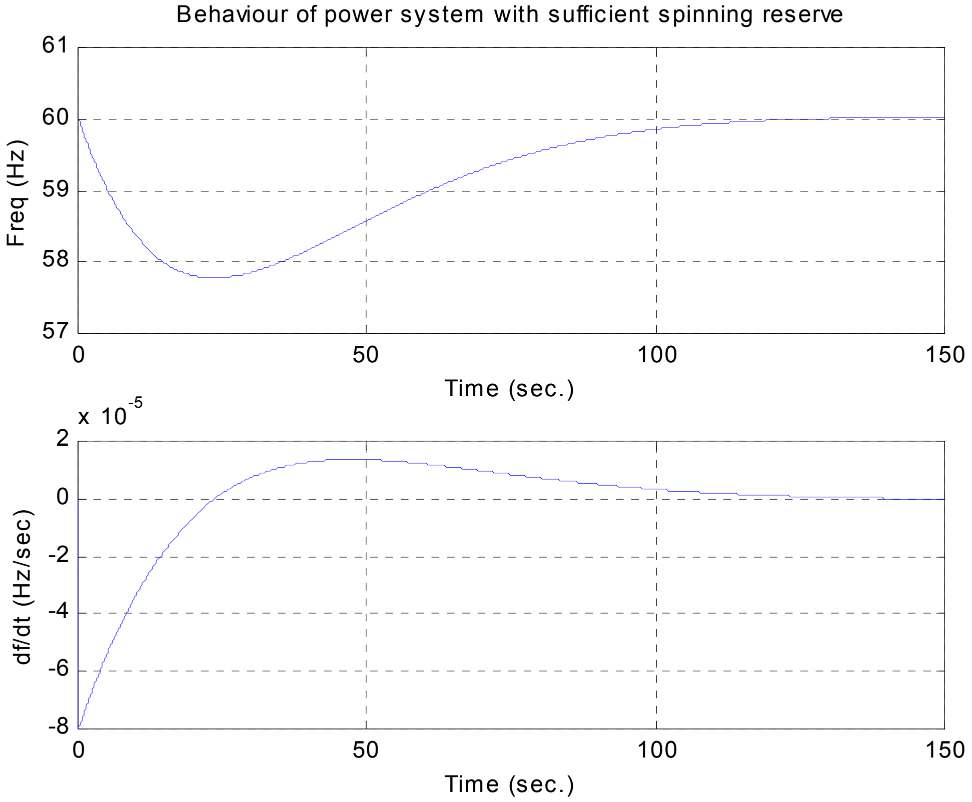

Figure 1 Frequency and rate of change of frequency plot

Underfrequency load shedding plans are based on studies of the dynamic performance of the system, given the greatest probable imbalance between load and generation. These studies are based on dynamic systems models and require appropriate modeling of the loads at different system nodes.

Considering the importance of the underfrequency load shedding and the fact that it leads to loss of supply to many utility customers, it is critical that the load shedding is optimized in order to limit the amount of tripped loads to an acceptable minimum. This is only possible if the models of the different components of the system are verified based on comparisons between the calculated and recorded system parameters.

As can be seen from Fig. 1 the duration of the abnormal frequency disturbance is in the range of 100 seconds. However, in the case of insufficient spinning reserve the frequency will stabilize at a level below the desired. To avoid this, frequency load-shedding will be executed. Since it is usually planned for worst case conditions, it may result in over-shedding, that will lead to load-restoration to restore the balance between the available generation and load. This process can take several hundreds of seconds.

Obviously the sampling rate of 1 minute and higher required for load-flow analysis is not sufficient to analyze a low-speed system disturbance such as loss of generation. A sampling rate in the range from 1 to several seconds will be appropriate for the recording of this type of event.

Since this is a system wide event, the time synchronization of all recording devices in the system is critical.

2.3. High speed-disturbance

One of the typical high-speed disturbance conditions in the electric power system is the power swing. It can result due to a sudden large change such as a permanent short circuit fault followed by unsuccessful reclosing and the tripping of the breakers at both ends of the faulted transmission line.

A recording of the behavior of the system can be used to analyze the transient-stability of the system, i.e. the ability of the system to stay in synchronism after large changes in system parameters, such as during fault conditions, switching off a parallel line or the loss of a large generator.

The analysis of such abnormal conditions in the system will require the recording of some pre-fault conditions followed by the complete record of the power swing condition. Such system events may have a length of many seconds and at the same time requires sufficient detail for future analysis. That is why the sampling rate should be typically in the range from one to several cycles per sample.

2.4. Waveform capture

Short circuit faults are one of the main causes for system disturbances, especially if they are not cleared quickly by the protective relays. Relay misoperation for faults outside of the zone of protection can further increase the possibility for a system blackout. Considering the fact that the instantaneous elements of protective relays operate within the range of ½ cycle to 2 cycles, it is obvious that the sampling rate of the recording should be in the sub-cycle range. Higher sampling rates are preferred, because they also show the details of the transient behavior of instrument transformers that might affect the operation of the protective relay.

The analysis of relay operation for different fault conditions requires the recording the pre-fault, fault and post-fault conditions, that can be followed by a second or even third fault if the reclosing is not successful. Such recording will typically cover several seconds. The sampling rate in this case will typically be in the range of 16 to 128 samples per cycle.

3. Recording Requirements for Distribution and Industrial Systems

Different forms of disturbance recording have been used for a long time at the transmission level of the electric power systems. The high cost of the centralized recorders restricted their use in distribution substations. The introduction of multifunctional protection and monitoring IEDs with recording capabilities, as well as the recognition of a need for better monitoring of the distribution system resulted in increased interest in different forms of recording in utility or industrial distribution substations.

3.1. Trends

Load-forecasting is becoming a very important task in distribution systems. It is a valuable tool that allows the optimal use of the available resources for tasks such as peak load control and centralized load-shedding.

Since the distribution of loads might not be equal between all three phases of a feeder, it is also important to be able to determine the maximum load unbalance, that eventually may lead to a ground fault overcurrent element misoperation.

All this information is available through a trend record that captures one sample of the selected electric quantities every several minutes, as specified by the user.

3.2. Low speed-disturbance

The sampling rate of one every few minutes is not sufficient for the recording of some power quality events such as power supply interruptions.

Supply interruptions are defined as events when one or more phases of a supply to a customer/group of customers are disconnected for a period exceeding 3 sec.

- Momentary Interruption: complete loss of Voltage (< 0.1 or 0.01 pu) on one or more phase for a time period between 0.5 cycles and 3 sec.
- Temporary Interruption: complete loss of Voltage (< 0.1 or 0.01 pu) on one or more phase for a time period between 3 sec and 1 min.
- Sustained Interruption: any interruption not classified as a momentary interruption.

From the above definitions it is obvious that the sampling rate for this recording should be in the range from 1 to several seconds.

3.3. High speed-disturbance

Certain power quality events are much faster than the power supply interruptions. For example, voltage sags and voltage swells are defined as:

Voltage dip (or sag):

A Voltage dip is a sudden reduction in the r.m.s. voltage, for a period between 1/2 cycle to 3 sec, of any or all the phase voltages of a single-phase or a polyphase supply. The duration of a voltage dip is the time measured from the moment the r.m.s. voltage drops below 0.9 per unit of declared voltage, to when the voltage rises above 0.9 per unit of declared voltage.

A dip/sag should be defined as a dip/sag "to x%" that is to the retaining voltage and not "by x%".

For example a dip to 20 % means that the retaining voltage was 20% of nominal (and not reduced by 20% compared to nominal)

The difference between a voltage dip and an interruption is that a dip starts when the voltage is reduces below 0.9 pu and is not reaching the interruption threshold (0.1 pu or 0.01 pu).

Voltage swell:

A Voltage Swell is defined as an increase in the r.m.s. voltage at the power frequency, for duration from 0.5 cycles to 1 minute. The typical magnitudes are between 1.1 and 1.8 pu. A swell is also quantified by the retaining voltage that is always greater than 1.0.

It is clear that the sampling rate should be in the range from one to several cycles per sample in order to be able to capture such a power quality event.

Pre-trigger and post trigger time should be selected by the user based on the specifics of the power quality monitoring philosophy.

3.4. Waveform capture

Close-in short circuit faults are usually cleared by an instantaneous phase or ground overcurrent protection element in a few cycles. Line end faults can take much longer – several seconds – depending on the system configuration and the coordination requirements that define the settings.

The analysis of the performance of the distribution feeder relays may require the fault condition to be replayed through a test set based on a standard waveform capture file format such as COMTRADE.

This requires the recording of the pre-fault, fault and post fault conditions with a sub-cycle sampling rate. The higher the sampling rate, the more accurate the replay of the fault conditions will be.

High sampling rates in waveform capture are also required for power quality analysis purposes – in the cases when the harmonic content of the monitored system parameters has to be calculated.

Typical values for harmonic analysis will be in the range of 128 samples per cycle. Such a sampling rate can be successfully used for protection testing purposes as well.

Fig. 2 shows the waveform capture for a fault with unsuccessful reclosing.

4. Recording

As can be seen from the examples described for the requirements of the recording of normal and abnormal conditions in transmission or distribution/industrial systems, the can vary significantly and cover a wide range from more than a hundred samples per cycle, to more than a minute between samples.

The analysis of all these different types of events in some cases require sampling of the waveform, while in other they need a periodic log of the RMS value of the monitored parameter.

That is why 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 quality event.

In order to allow the user to “zoom-in”, all recording types 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.

The user should be able to enable or disable the different types of recording as required by the specifics of the application.

The following three main types of recording are identified based on the above discussed requirements:

4.1. Waveform recording:

User programmable pre- and post-trigger should be available.

The trigger should be able to be defined as a threshold on any measurement and the user should be able to define multiple independent triggers.

Options to trigger High-speed disturbance recording when a Waveform capture is triggered is achieved by using the same trigger with different recording modes.

Extended Post-trigger recording should be available if there is a re-trigger or a new trigger.

4.2. High- and low-speed disturbance recording:

High-speed or low-speed disturbance recording is intended for capturing high-speed power quality events such as voltage sags or voltage swells during short circuit faults on the transmission or distribution system, or other events based on the calculated and updated every 1/4 of a cycle or 1 cycle measured or calculated system parameters.

The disturbance recording IED stores the values of a user defined set of parameters every log interval.

The setting range is dependent on the available memory in the IED, for example from 1 to 3600 cycles and can be changed with a step of 1 Cycle.

The user should be able to specify Pre-trigger and Post-trigger time in samples. The increment is 1 sample. The sum of the Pre-trigger and Post-trigger should be equal to or less than the selected record size (for example 3072 samples maximum).

The disturbance record file should be stored in non-volatile memory, allowing for its retrieval even after the power has been cycled to the instrument.

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.

For each parameter the user should be able to select the recording of the current sample of the recorded quantity or to record the minimum, maximum, and average values that occurred during the previous interval recorded.

When recording is complete, a status bit should be set, indicating the availability of a Disturbance Record. This allows the analysis software in the substation HMI to automatically extract and store the disturbance records on its hard drive for further analysis if necessary.

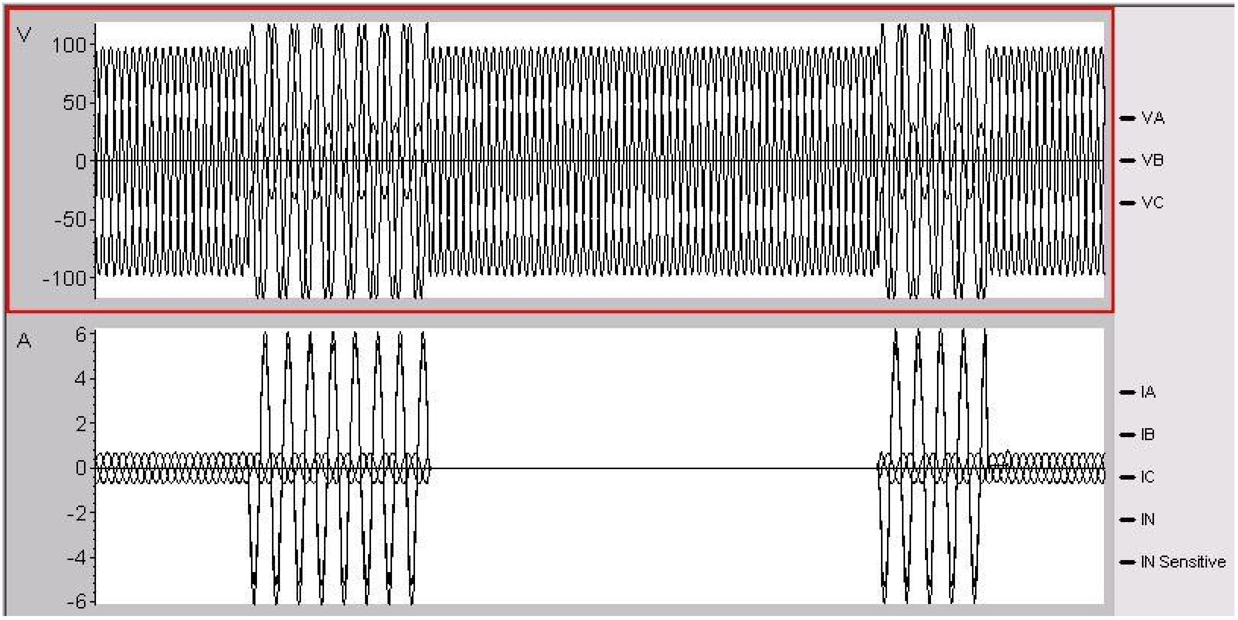

Figure 2. Waveform capture record from a single phase fault with unsuccessful reclosing

The combination of waveform capture and high- or low-speed disturbance recording triggered by the same power quality event 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.

4.3. Periodic Measurement Logging:

The recording device should be able to store the values of a defined by the user set of parameters every log interval. This interval defines the sampling rate of a trend recording 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.

The measurement log record file should be stored in non-volatile memory, allowing for its retrieval even after the power has been cycled to the instrument.

5. 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 results in a very efficient complete solution that meets all requirements for a substation automation system. It allows the distribution of protection, control and monitoring functions between multiple devices at the different levels of the hierarchy. The system has two or three levels depending on the type and size of the substation, as well as the user requirements.

Fig. 3 shows a simplified one-line diagram of a substation with protection and power quality monitoring or disturbance recording devices installed on each transmission line transformer and distribution feeder.

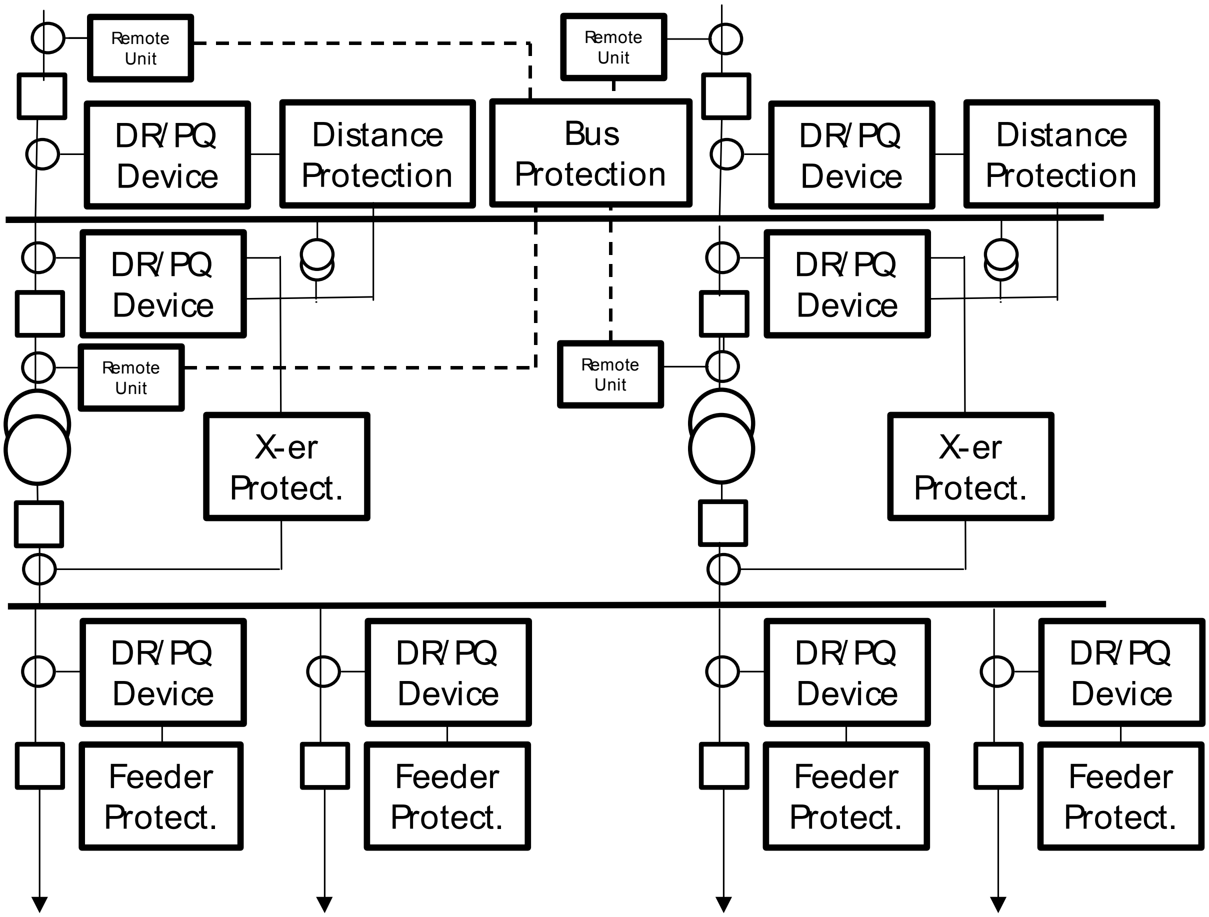

Fig. 3 Protection and power quality monitoring or disturbance recording devices in a typical distribution substation

The advantage of this approach is that it provides primary and backup recording functionality in the integrated 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. Their sampling rate is much lower – typically 16 to 64 samples per cycle for the waveform capture and without any disturbance recording capabilities. However, some devices allow waveform capture of more than 10 seconds, that will be sufficient for capturing most power quality events.

These sampling rates might not be appropriate for some harmonic calculations, but they are still OK considering that they perform backup functions only.

The functional architecture of a substation automation system shown in Fig. 4 has a three 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.

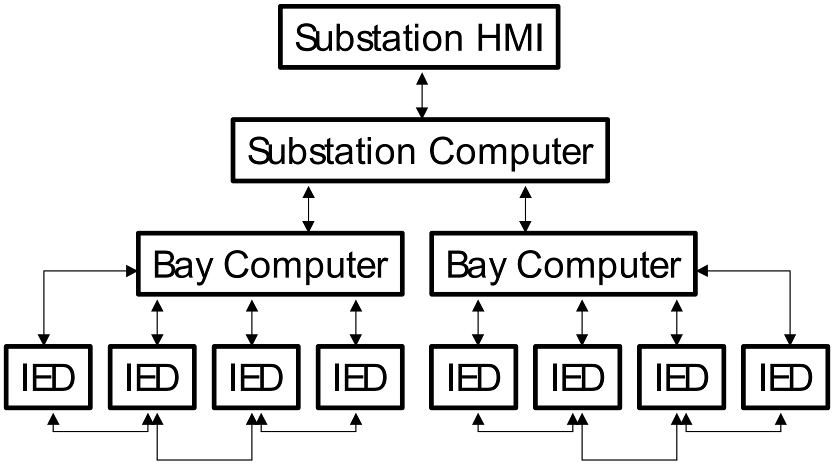

Figure 4. Simplified Substation Automation System architecture diagram

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 computers 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 quality analysis functions.

The event logs from multiple devices during voltage sags, swells and other power system parameters deviations can be analyzed at the substation level in order to determine the cause of the event and its effect on different customers supplied with power from the substation.

A simplified diagram of the communications architecture for such a substation automation system is shown in Fig. 5.

This is an architecture that uses switches instead of hubs in order to eliminate the effects of collisions on the performance of protection functions based on high-speed peer-to-peer communications between the different IEDs.

High-speed communications are also used for distributed recording functions as described in the next section of the paper.

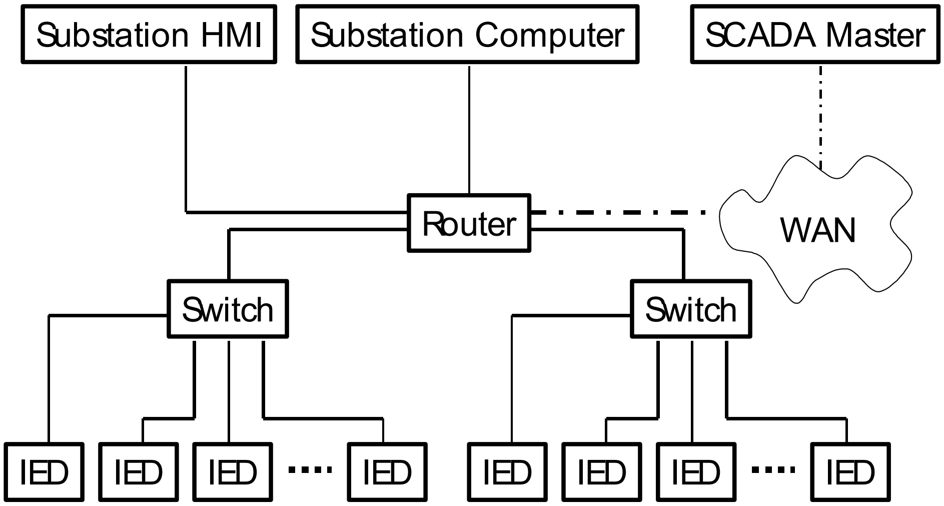

Figure 7 Simplified communications architecture

6. High-speed Peer-to-Peer Communications

The peer-to-peer communications in an integrated substation protection and control system are based on what is defined as a GOOSE [1]. This is a Generic Object Oriented Substation Event (GOOSE) and it is based upon the asynchronous reporting of an IED's functional elements status to other peer devices enrolled to receive it during the configuration stages of the substation integration process. It is used to replace the hard wired control signal exchange between IED's for interlocking and protection purposes and, consequently, is mission sensitive, time critical and must be highly reliable.

The associated IEDs receiving the message use the contained information to determine what the appropriate protection response is for the given state change. The decision of the appropriate action to GOOSE messages and the action to take should a message time out due to a communication failure is determined by local intelligence in the IED receiving the GOOSE message. It can be used to trigger recording based on GOOSE messages from different protection or power quality monitoring IEDs.

The table below includes the common components used to facilitate the GOOSE Class Object.

Considering the importance of the functions performed using GOOSE messages, UCA defines very strict performance requirements. The idea is that the implementation of high speed peer-to-peer communications should be equal to or better than what is achievable by existing hard-wired technology. Thus the total peer-to-peer time should not exceed 4 ms [1].

Another important requirement for the GOOSE messages is very high reliability. Since the messages are not confirmed, but multicasted, and considering the importance of a message such as Initiate Breaker Failure Protection or Fault in Reverse Direction, there has to be a mechanism to ensure that the receiving IED's will receive the message and operate as expected. To achieve a high level of reliability, messages will be repeated as long as the state persists. To maximize dependability and security, a message will have a time to live which will be known as “hold time”. After the hold time expires the message (status) will expire unless the same status message is repeated or a new message is received prior to the expiration of the hold time.

Table 1 GOOSE structure

Common Components Required for GOOSE		
Name	**Description**	**Data Type**
Sending IED	Sending IED IDENT	IDENT
t	GOOSE Timestamp	BTIME6
SqNum	Message Sequence Number	INT16U
StNum	Event Sequence Number	INT16U
HoldTim	Time to Wait before RS	INT16U
BackTim	Time since Event	INT16U
PhsID	Identifies Faulted Phases	INT16U
DNA	Protection DNA	BSTR64
UserSt	User defined Bitstring, used in bit pairs	BSTR256

The repeat time for the initial GOOSE message will be short and subsequent messages have an increase in repeat and hold times until a maximum is reached. The GOOSE message contains information (Table 1) that will allow the receiving IED to know that a message has been missed, a status has changed and the time since the last status change.

In order to achieve high speed performance and at the same time reduce the network traffic during severe fault conditions, the GOOSE message has been designed based on the idea to have a single message that conveys all required protection scheme information regarding an individual protection IED. It represents a state machine that reports the status of the functional elements in the IED to it’s peers. The GOOSE uses a low-overhead communication protocol to minimize the state-to-message transmission time.

To allow further customization of the GOOSE messages, individual applications can map other status points to the User Defined bit pairs UserSt.

The GOOSE messages are used in a distributed disturbance recording system in order to allow inter-triggering of records between different IEDs in the substation automation system. For example, it is possible that there are limitations in the number of triggers available in the recording IEDs that are based on thresholds for selected system parameters. When a protection IED, bay controller or a substation computer detects and event that requires some specific type of recording, they will immediately send a GOOSE message to a group of recording IEDs to trigger recording.

Each recording IED will have to be configured to subscribe to receive GOOSE messages from different protection IEDs. Recordings of each of the types described above should be triggered by a different bit pair in the GOOSE message sent by the protection IED.

7. Time-synchronization

One of the main requirements for a distributed disturbance recording system is the ability to properly synchronize the different recording devices. This will ensure that all events or disturbance records are time-stamped with sufficient accuracy, so that the analysis tools can generate the sequence of events record for the whole substation and align the disturbance records from different devices for further analysis.

Time synchronization of the different IEDs can be achieved using several common methods. One is to manually synchronize the IED clock to the clock of a laptop connected to a serial port of the IED. It is obvious that this method of synchronization will not meet the accuracy requirement for any of the typical disturbance analysis applications. That is why a distributed disturbance recording system needs to include a master time device that generates a standard time code.

Several vendors manufacture such master time devices and support different standardized time synchronization protocols. IRIG-B is one of the more commonly supported standard time code formats that has been widely accepted by the electric utilities and is supported by most IED installed in substation automation systems.

IRIG (InteRange Instrumentation Group) standards consist of a family of serial pulse time clock standards. They were initially developed for use by the U.S. Government for ballistic missile testing. There are several Time Code Formats within the family such as A, B, E, G, and H. Each Time Code Format has its own unique bit rate.

There are two common ways of synchronizing various devices to the same clock source:

- Synchronization over direct connection
- Network synchronization

Synchronization of IEDs over direct connection requires each device to have an IRIG-B communications port in order to connect it to the master time device. This synchronization scheme can be expanded such that two devices half a world apart could be synchronized to within fractions of a second if each is connected to an accurate local time master.

Having a permanently connected IRIG-B source provides the most accurate IED clock with a typical clock error of less than 10 microseconds. However, the failure of the master time device is a possibility that should be considered in the design of the time-synchronization feature of the IED in order to ensure accurate time-stamping even in the cases of loss of the master.

A disadvantage of the direct time-synchronization is the requirement for an IRIG-B input for each IED and the hard wiring between the individual devices and the master. The network synchronization method eliminates this problem by allowing the IEDs real time clock to be synchronized over the substation LAN with the network time-synch master.

An important requirement for the implementation of time-synchronization in the recording IEDs is to ensures that time always flows forward, even when time sync messages indicate that the IED is ahead of the Master. This assures that events are always time-stamped in the order in which they occurred.

6. Conclusions

Different types of abnormal system conditions at the distribution, sub-transmission and transmission levels of the power system have specific characteristics that are reflected in the requirements for their recording for further analysis.

Four different types of records with appropriate sampling rate ranges and record length are identified:

- Load profiles
- Low-speed abnormal system conditions
- High-speed abnormal system conditions
- 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.

Protection, monitoring and recording devices are multifunctional IEDs that can be integrated into a hierarchical disturbance recording system. The IEDs and a substation computer are connected to a substation local area network.

High-speed peer-to-peer communications are used to trigger distributed recording of faults or other abnormal power system conditions.

Reference:

1. Generic Object Models for Substation and Feeder Equipment (GOMSFE), Version 0.92