Distributed Web-based Systems for Recording of Wide Area Disturbances

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INTRODUCTION

One of the main issues with the analysis of a wide area system event such as the August 14, 2003 blackout is the type and quality of available records. The comments by NERC and other officials, that there were thousands of records to be analyzed was correct. However, even if there are multiple records of different kinds, it doesn't mean that a conclusion of the cause of the blackout can be reached. Keeping in mind that there were multiple events such as tripping of lines, loss of generation, power swings, the records from digital relays will not be very useful for the analysis of the disturbance, except to determine the cause of tripping of a transmission line. The effect on the system can be analyzed based on long high- or low-speed disturbance records that show the voltage, frequency, active and reactive power and other system parameters over many seconds or even minutes.

Even if such records are available from multiple devices located in different parts of the wide area affected by the disturbance, they may create the wrong impression about the development of the disturbance if they are not properly synchronized. According to different news reports, this is one of the problems that the experts analyzing the blackout were experiencing.

The paper discusses the requirements and describes a web-based system for wide area disturbance recording. The primary recording devices are specialized monitoring and recording devices, while the backup recording is provided by the protection IEDs and the substation level of the substation automation system. The distribution of recording modes between these three components of the distributed recording system is described.

The communications architecture of a web-based distributed system for wide area disturbance recording and methods for remote access are presented later in the paper.

The accurate time synchronization, the availability of waveform, high- and low-speed disturbance recording makes such a system the preferred choice for anyone that needs to install a wide area disturbance recording system. Requirements and solutions for extended memory address the need for the user to be able to record hundreds of different events occurring over a short period of time without filling up the memory and overwriting earlier records.

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.

The records can be later used to further identify the details of specific events that resulted in the deterioration of the situation that ended in the final several seconds of the blackout. Shutdown of generators, operation of under-frequency load shedding, tripping of transmission lines during faults or power swings can be analyzed using simulation of the system dynamics or directly replaying the records through protection test devices.

The experience from the analysis of the blackout, as well as many other system events in the past, shows that all of the above is possible only if the records meet certain requirements, i.e. if we can answer the second question.

Whatever the type of record available, it is extremely important that it is time-stamped with sufficient accuracy. It is widely accepted that a 1 millisecond resolution is in general sufficient to allow the generation of a system-wide event log. But the fact that a device can time-stamp an event that it detects will still be meaningless if it is not accurately time-synchronized.

The answers to the second question will be different depending on what we need to analyze.

If we consider the start of a wide area disturbance, it is usually caused by a short circuit fault, followed by protective relay operation and tripping of one or more system elements. For example a cross-country line fault will result in tripping of two transmission lines, that may lead to a system disturbance.

The analysis of this initial phase will require the recording of the current and voltage waveforms at different locations around the system, as well as accurate capturing of the change of state of breakers auxiliary contacts and protection Trip outputs.

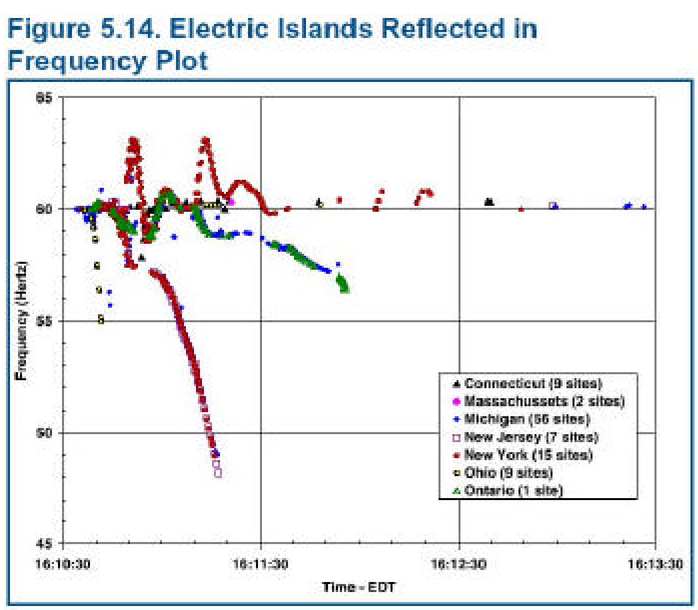

Fig. 1 Frequency plot from NERC August 14, 2003 Blackout Report [1]

If tripping of line, transformer or bus breakers was the result of relay misoperation, more detailed information, such as Start or Operate of individual protection functions will need to be recorded and reported.

The analysis of the behavior of special protection systems or primary system elements during the next phase of a wide area disturbance imposes recording requirements that are quite different.

Since the records can be used for different purposes, 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.

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

- Waveform recording
- High-speed disturbance recording
- Low-speed disturbance recording

All of the above should record not only selected analog system parameters (currents, voltages, frequency, power, etc.) but also binary signals.

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 the details of the transitions from one state to another are recorded in the waveform capture.

The events on August 14, 2003 showed that a wide area disturbance may develop over a couple of hours and is the result of multiple events, such as loss of generation, tripping of transmission lines, operation of protective relays, operator control action, etc. This requires the recording devices to have extended memory - for example 256 MB, in order to ensure that no records will be lost due to overwriting when multiple events occur before the records are retrieved.

It is also important that the recording devices have multiple binary inputs that will allow the recording of change of state of breakers or other switching devices, as well as to accurately capture the operation of electromechanical, solid state or microprocessor based protection and control devices.

DISTRIBUTED RECORDING

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. 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 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. Such events are 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 variations. 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, 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 events 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 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.

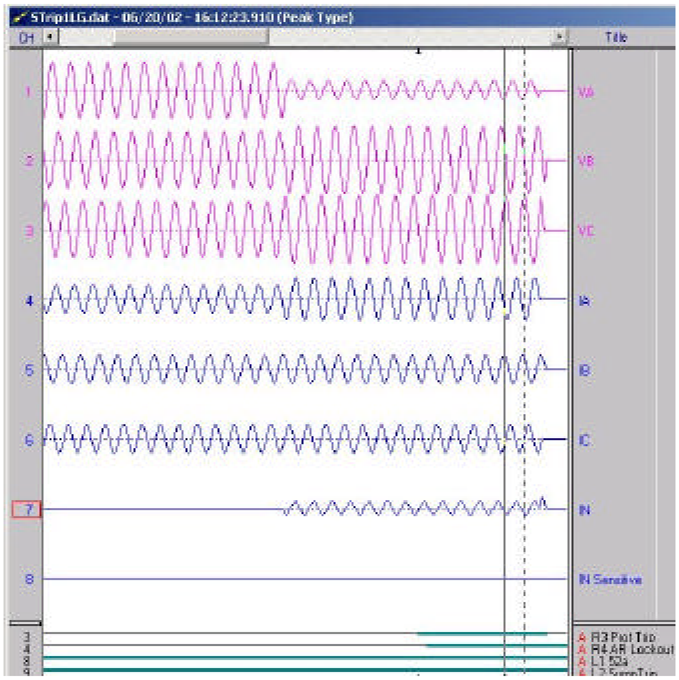

Fig. 2 Waveform record including state change information

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.

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.

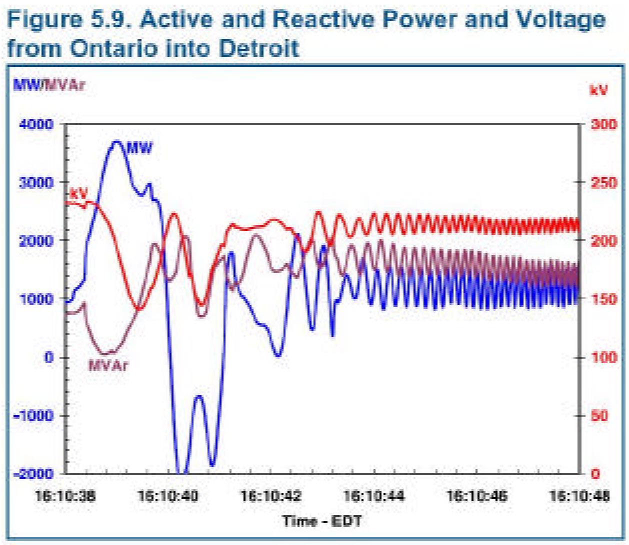

Fig. 3 High-speed disturbance record

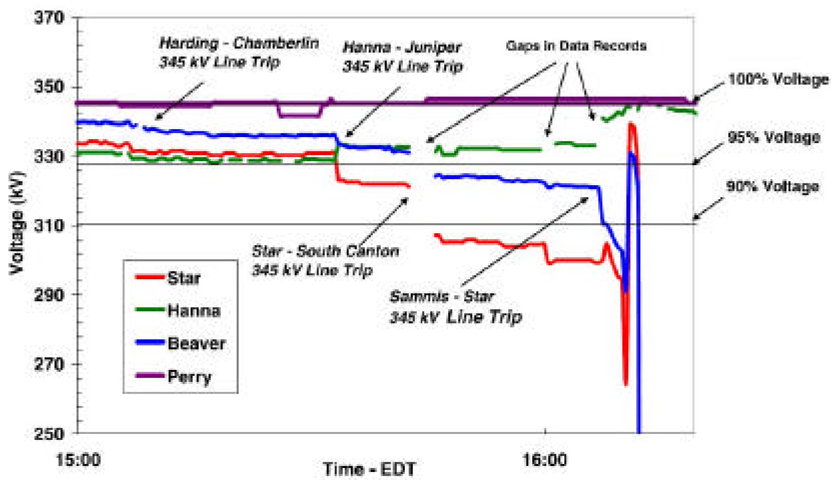

Fig. 4 Low-speed disturbance record

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.

The protocol defines file transfer services that provide the functionality for transferring files from the IED to a substation client. FileDirectory service can be used by a client to obtain the names and attributes of a specific file or all files stored in the server's memory.

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. 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. Since wide area disturbances in many cases are analyzed based on the rms values of the voltages or the system frequency, this will require further processing of such waveform files.

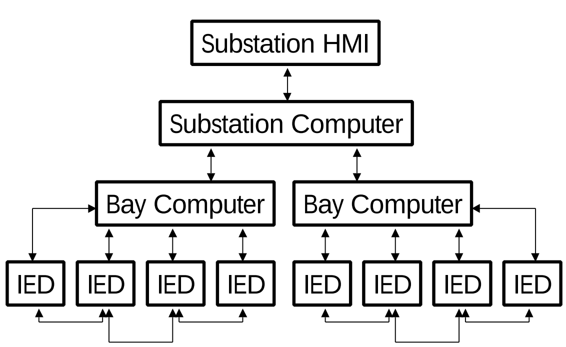

Fig. 5: Simplified SAS architecture diagram

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. 5 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.

A simplified diagram of the communications architecture for such a substation automation system is shown in Fig. 6.

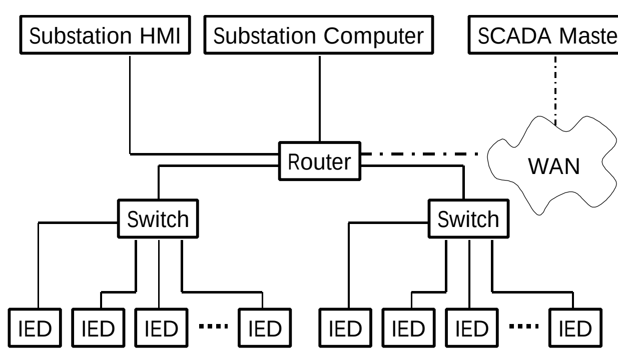

Fig. 6: Communications architecture

This is an architecture that uses switches instead of hubs in order to eliminate the effects of collisions on the performance of protection functions or recording cross-triggering based on high-speed peer-to-peer communications between the different IEDs. However, for small substations with limited number of IEDs, the use of hubs might be acceptable.

One advantage of distributed recording in substation automation systems is the availability of primary and backup recording devices or functions (see the table below).

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

TIME-SYNCHRONIZATION

One of the main requirements for a distributed monitoring and recording system is the ability to properly synchronize the different 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 or electric power system 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 monitoring and 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 IEDs installed in substation automation systems. IRIG (InteRange Instrumentation Group) standards consist of a family of serial pulse time clock standards. 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 an 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 where the master is lost.

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 using the methods specified by the protocol. The time synchronization model is based on UTC synchronized time provided to the applications located in server and client substation IEDs. The resulting time accuracy in the whole system should be +/- 1 ms for time tagging of events and +/- 0.1 ms for time tagging of zero crossings and data for distributed synchrocheck.

WEB ACESS

The main interface in an integrated substation protection, control, monitoring and recording system is provided by the HMI that represents the upper level in the substation hierarchy. It includes multiple applications designed to perform specific tasks as required by the utility.

The PCMR (Protection, Control, Monitoring and Recording) system requires a memory resident SCADA software package with a wide range of SCADA features including:

- Real-time Data Viewing
- Event and Alarm Logging
- Real-time Trending
- Historical Data (periodic or by exception)
- Abnormal and Not In Service Summaries
- ASCII Import/Export of Data
- Flexible Calculator Package
- Multiple Limit Checking
- Audible Annunciation

When the PCMR system is integrated into a mail service, the alarms may also be issued using common e-mail services to other mail addresses, pagers, or even cell phones.

Other applications that are part of such complete solution include IED setting programs, automatic record extraction programs, analysis tools, programmable scheme logic editing tools, GOOSE configuration tools, COMTRADE viewers, etc. as required by the specifics of the protection, monitoring and control system implemented in the substation.

The substation HMI is not only used for visualization of data or local control in the substation, but also as a gateway or front end to a remote SCADA master. It also can provide remote access to different corporate clients over the utility Wide Area Network.

One of the main problems with any integration system is the development of the HMI. The concept of a modular Web enabled system based on the integration of multifunctional IEDs in pre-engineered solutions allows significant reduction in the engineering and the overall cost of the system.

This is generally achievable for small distribution substations, because they have a standard configuration. Still, the user may have requirements for customization in order to develop a “utility standard” HMI. This requires the availability of engineering tools such as a display builder. That allows customization of displays and graphical representation of data and alarms. The displays may be interconnected through hot links for navigation between views.

Since there are requirements for local (at the substation) or remote (through the utility WAN) access to substation data, state-of-the-art energy management systems are equipped with tools that allow the simultaneous development of different displays.

When a display is built and linked to the database two viewable images are automatically generated. One of the images can be locally displayed on an optional user display unit and does not require a browser to be viewed. The second image is created using HTTP, which means that the display may be viewed with Microsoft’s Internet Explorer from a remotely connected PC. These displays may be viewed locally on an Ethernet connection or remotely using an optional modem for external access via a phone line.

Fig. 7 shows the substation one-line diagram from the Web browser interface.

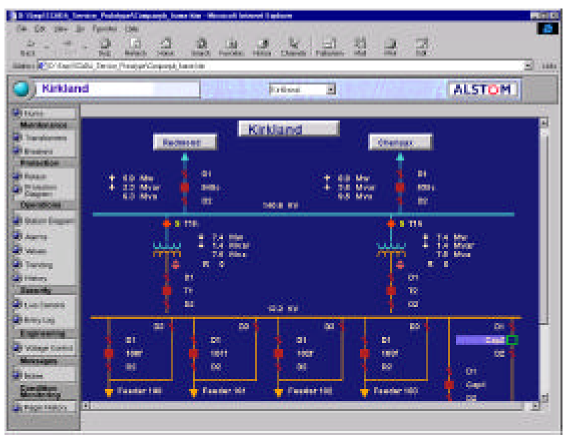

Fig. 7: Web interface to substation one-line diagram

For substations that are remote and difficult to access it is important to have tools that provide different views of the substation yard – for example video or infrared cameras.

Fig. 8 shows a page with a view of the yard from a substation camera in the center. On the left side of the page are the controls that allows the user to select other screens such as the substation one-line diagram, load profiles, the communications architecture, alarm and event logs, etc.

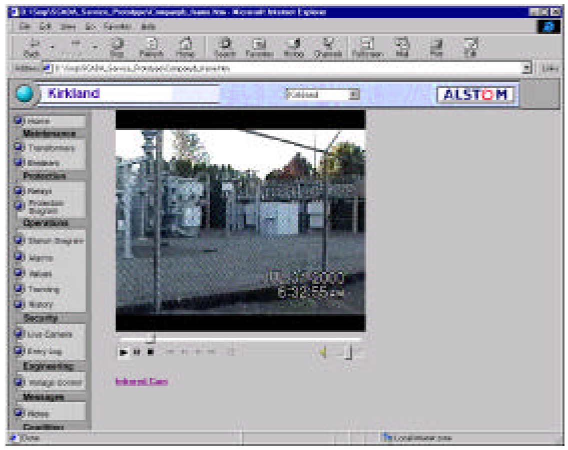

Fig. 8: Web Camera view of substation yard

The extraction of different records from the IEDs is achieved using another software tool that runs on the substation computer under the Process Starter. The extracted files are saved on the substation computer's hard drive for analysis or viewing. Local access to the analysis software is available through icons on the toolbar of the user interface.

Web access to the different records available from the multifunctional IEDs in the substation, as well as to the analysis tools installed on the substation computer can be achieved using remote control software. In order to allow a remote user to make a connection to the substation computer from a remote engineering station, both computers (see Fig. 9 - both are shaded) must be running the remote control software. The substation computer must be configured as a "host", and the engineering station computer must be configured as a "remote".

The remote user can view the disturbance or waveform records stored on the substation computer's hard drive using a COMTRADE viewer or other analysis tools installed on it (if he/she has permission to access them).

The substation computer is configured to allow remote connection only from authorized users. The configuration controls who can connect to the computer and what level of access the remote user should have. The exchange between the remote engineering station and the substation host computers is called a remote control session.

This web based remote access method has significant advantages. First of all, when the remote user runs a software program during a remote control session, the actual processing is performed on the substation host computer.

Because only minimal data needs to be transferred between the two computers over the web, remote control results in faster performance and minimizes the risk of losing data.

The second important issue is the security of the remote control session. Since the record viewed might be of sensitive nature, it is critical that unauthorized clients are not allowed to connect to the substation computer.

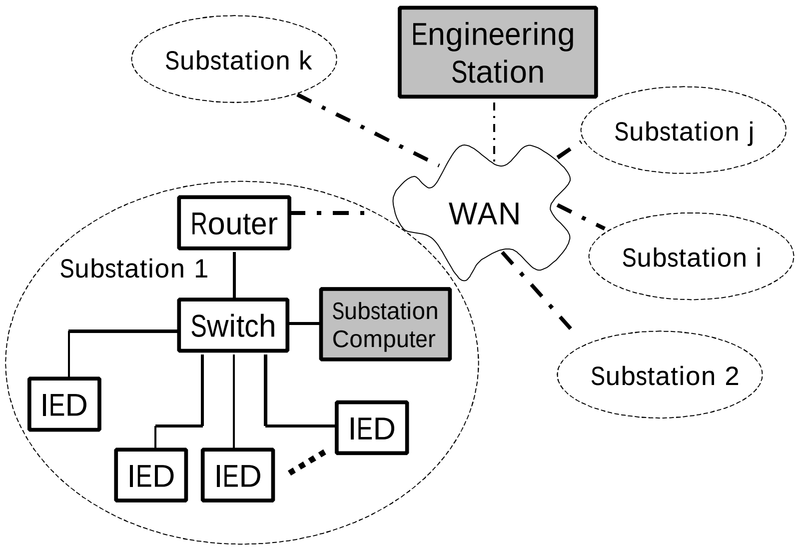

Fig. 9: Remote Web access from an Engineering Station

Some features that ensure the security of the session are as follows:

- Use of advanced authentication methods
- Ability to track files and executables opened during a host session
- Ability to lock a configuration set to prevent tampering with the remote control software configuration files, executables, and registry settings
- Use of a combination of encryption methods to ensure that the data exchanged cannot be read or altered by unauthorized users while in transit.

A direct method for access of waveform and disturbance records is available for IEDs that have a built-in FTP (File Transfer Protocol) server. FTP is used on the Internet for exchange of files and is based on TCP/IP. In this case the remote user must enter in the FTP Client application (for example Internet Explorer) the IP address of the IED that acts as FTP server. Authentication methods can be used to ensure authorized access to the file transfer.

CONCLUSIONS

The integration of multifunctional IEDs with protection and monitoring functions in UCA 2.0 or IEC 61850 substation automation systems allows the implementation of web-enabled distributed systems for recording of wide area disturbances.

The distributed recording functions are based on the models and services specified by the protocol. The system allows the integration of UCA/IEC 61850 compliant or legacy devices.

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.

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

- 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.

Secure web access for viewing or retrieval of different records is possible during remote control sessions between the remote engineering station and the substation host computer. Direct access for retrieval of files is allowed when the recording IEDs have a built-in FTP server.

REFERENCES:

[1] U.S.-Canada Power System Outage Task Force, “Interim Report: Causes of the August 14th Blackout in the United States and Canada”, Nov. 2003 [Online]. Available: http://www.nerc.com/