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INTRODUCTION

Energy usage is a significant product cost component for many industrial and manufacturing facilities. Managing the availability, delivery, reliability, and allocation of energy resources has historically been a major challenge for plant and facility managers. As an example, the electrical transmission and distribution networks in many mills rival those of most municipalities in regard to size and complexity but traditionally have included only limited integration or online monitoring within the manufacturing control system. This limitation existed, at least in part, because the protective relays and meters were electromechanical vintage and did not include communications or recording capabilities.

Either due to equipment end-of-life or facility improvement projects, many upgraded plant substations now include modern intelligent electronic devices (IEDs), which not only perform much better than their predecessors in their primary function but also enable significant improvements for communications and integration. Convenient and flexible methods exist for users to view and benefit from the information produced by these IEDs. Other papers describe how this is accomplished.[1]

Beyond electrical power system information, many personnel within the facility and organization require coherent process data in order to perform their jobs. Equipment operators and maintenance groups are the primary audience for distributed control systems (DCSs) and human-machine interface (HMI) displays for ongoing command, control, and analysis of process performance. Extending the functions of operational data displays, process historian systems have gained in popularity by providing business intelligence and a holistic view of entire processes to many groups within a mill. These groups include not only operations personnel but also staff in areas such as accounting, planning, and purchasing.

Process historians enable a number of valuable use cases that users were previously unable to accomplish. These use cases include aggregation of process and business information in interoperable repositories, access for users who lacked these data in the past, consolidation of infrastructure services and reporting tools in one location, and native support for mobile and desktop viewing of reports. Many historian repositories include time-series data commonly used in supervisory control and data acquisition (SCADA) as well as other batch and associated records.

Because modern IEDs can continually monitor and report the status of plant electrical systems, these data fit well within existing historian repositories. Additionally, these devices record and store specialized reports based on predetermined events that may intermittently occur within the power system. One type of report is composed of high-speed oscillographic data, which are used by the electrical staff to diagnose the root cause of electrical faults. The Institute of Electrical and Electronics Engineers (IEEE) created a standard file format for these reports that further simplifies the process of analyzing faults recorded by IEDs from multiple manufacturers.

Within a mill environment, IEDs function as useful control and monitoring elements within the overall control system. The continuous metering and status information from the IEDs within the power system fits very well into HMI and historian use cases. This paper addresses how the event report data from IEDs can also be transferred into and stored in process historians. The nature and format of event reports are presented, and some of the benefits of combining high-speed event data with other time-series information are explored.

INTRODUCTION TO PROTECTIVE RELAYS AND IEDS

Electrical generation, transmission, and distribution networks (whether bulk commercial systems or dedicated industrial networks) are complex systems that require specialized, continuous, and automatic monitoring and protection. Traditionally, electromechanical relays performed this function. They directly measure voltages and currents in the power system by means of instrument transformers that reduce the measured signals to appropriate levels for connection to the terminals of the relay. Each relay functions based on predetermined operating principles. For example, an overcurrent relay measures the primary phase current in the protected circuit and compares it to a setting of nominal or safe circuit current. If the measured current exceeds the setting, then an output contact in the relay asserts in order to trip a circuit breaker and disconnect the protected line from source power. Figure 1 shows these electrical connections in a simplified diagram. Many other types of relays exist that evaluate circuit parameters in many different forms; overvoltage, undervoltage, ground fault, differential, and distance (impedance-based) relays are examples.[2]

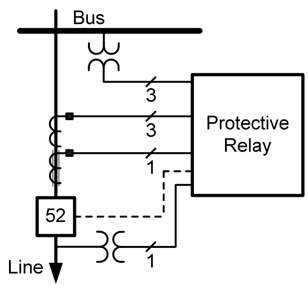


Figure 1. Protection one-line diagram for a feeder relay

Limitations of Electromechanical Relays

In order to properly protect high-voltage substations and lines from various faults, electromechanical relay panels (as shown in Figure 2) include many electromechanical relays, each with its own protection function, for each protected electrical apparatus. Because of the mechanical nature of these relays, users must remove them from service on a regular basis (usually once per year) for testing and calibration. Because these types of relays do not include self-check capability, users are not aware of a misoperating relay unless a fault occurs or a maintenance tester discovers the problem. Additionally, these relays provide no communications or integration functionality. In order to gain monitoring, control, and reporting functions, designers have commonly added remote terminal units (RTUs) and digital fault recorders (DFRs) to the system. These additional instruments increase the cost, complexity, and likelihood of failure within the protection, control, and monitoring network.

Figure 2. Electromechanical relay panel

Electrical System Upgrades

Due to the age, performance, or cost of these systems (or a combination of all of these factors), many plant electrical managers have been replacing electromechanical protection panels with modern microprocessor-based relays and power system monitoring devices (classified as IEDs), which overcome many of the challenges inherent to previous designs. For example, IEDs can evaluate and operate on many protection functions within a single physical device. A single relay can provide multiple phase current, voltage, and ground disturbance detection elements. As shown in Figure 3, protection panel designs employing IEDs are much simpler and inherently less expensive because one device replaces multiple single-function electromechanical relays. IEDs include automatic self-check and alarm functions and require little or no ongoing maintenance. Microprocessor-based relays also have provisions for capturing a record of electrical disturbances or heavy load conditions that are approaching fault thresholds. Not only do these capabilities create cost savings and eliminate electrical shutdowns, but they also provide immediate notification of relay failures before a power system fault occurs (allowing for immediate corrective action, repair, or replacement).[3]

Figure 3. Microprocessor-based relay panel

Modern relays, meters, and monitoring devices natively include active communications (Ethernet and serial) for convenient monitoring and control without additional dedicated devices. Relevant for this paper is the fault recording capability included with many modern microprocessor-based protective relays, meters, and equipment monitors. The following sections of this paper address the nature of fault records and methods to retrieve these data from the relays.

OSCILLOGRAPHIC EVENT REPORTS

Modern microprocessor-based IEDs natively record and store a great amount of information that helps control and monitor the power grid in a safe and reliable manner. IEDs send control, status, and alarm signals, such as a relay trip signal or circuit breaker open/close status, directly to the SCADA system via a high-speed dedicated communications network. The SCADA system is continuously monitored by operators who are responsible for making decisions about system operation and restoration. The IEDs also provide fault recording capability and store oscillographic event reports that are analyzed by protection engineers after a fault occurs in the system.

Information sent from the IEDs to SCADA is used for monitoring and immediate restoration of the system, whereas oscillographic event reports are used for diagnosing the fault, testing, measuring performance, and identifying issues that can potentially cause problems in the future. Oscillographic reports indicate whether the relay and all the associated components of the protection system are installed and have operated correctly.[4]

Overview of COMTRADE Report Format

To avoid confusion and provide a standard format for all manufacturers, the Power System Relaying Committee (PSRC) of the IEEE Power and Energy Society introduced a file format, called IEEE C37.111-1999, designed to capture analog and digital signal samples from microprocessor-based relays. This format is also known as COMTRADE (Common Format for Transient Data Exchange). The standard specifies a format consisting of three different files that are combined to create one oscillographic event report. These files use the following extensions:

- CFG is a configuration file.
- HDR is a header file.
- DAT is a data file.

A CFG file contains information such as the signal names, start times of the samples, number of samples, minimum and maximum values, scaling, and timing data.[4]

The data in a DAT file contain digital time-stamped samples of instantaneous values from both analog and digital channels. The analog channels are generally voltages and currents, while the digital channels are statuses of relay input and output contacts.

An HDR file is an optional file that contains information on the event that is recorded in the DAT file. This includes information such as the event type, fault location, data source, time source, and power system conditions before the disturbance. Figure 4 shows examples of all three files.

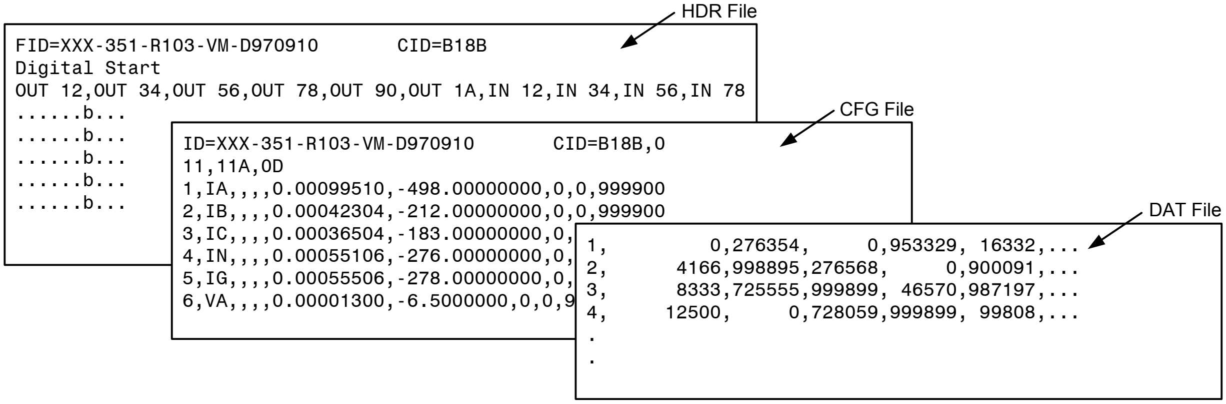
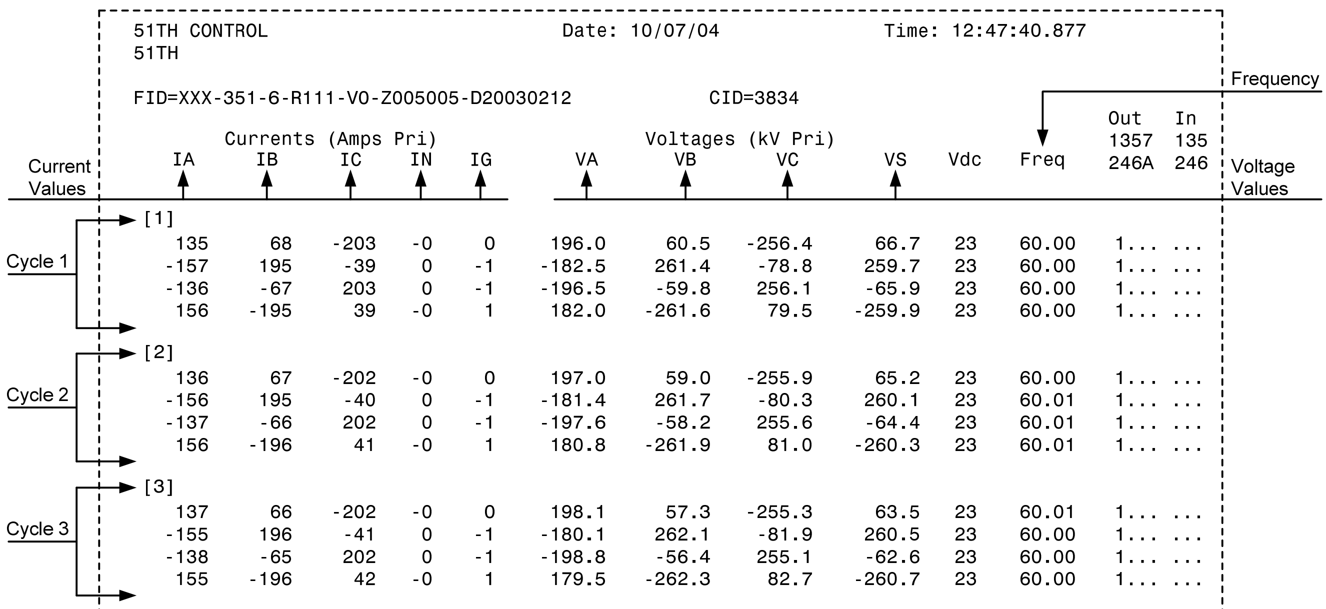


Figure 4. COMTRADE files

Figure 5 shows a segment of an oscillographic event report in ASCII format. It is a standard 4-samples-per-cycle event report showing current, voltage, and frequency values for each cycle. Each sample is represented as a row of data points.




```
51TH CONTROL                       Date: 10/07/04          Time: 12:47:40.877
51TH

FID=XXX-351-6-R111-VO-Z005005-D20030212           CID=3834
                                                                        Out   In
          Currents (Amps Pri)              Voltages (kV Pri)            1357  135
   IA     IB     IC    IN    IG      VA      VB      VC      VS   Vdc   Freq   246A  246

[1]
   135     68   -203   -0     0    196.0    60.5  -256.4    66.7   23  60.00  1... ...
  -157    195    -39    0    -1   -182.5   261.4   -78.8   259.7   23  60.00  1... ...
  -136    -67    203    0    -1   -196.5   -59.8   256.1   -65.9   23  60.00  1... ...
   156   -195     39   -0     1    182.0  -261.6    79.5  -259.9   23  60.00  1... ...
[2]
   136     67   -202   -0     0    197.0    59.0  -255.9    65.2   23  60.00  1... ...
  -156    195    -40    0    -1   -181.4   261.7   -80.3   260.1   23  60.01  1... ...
  -137    -66    202    0    -1   -197.6   -58.2   255.6   -64.4   23  60.01  1... ...
   156   -196     41   -0     1    180.8  -261.9    81.0  -260.3   23  60.01  1... ...
[3]
   137     66   -202   -0     0    198.1    57.3  -255.3    63.5   23  60.01  1... ...
  -155    196    -41    0    -1   -180.1   262.1   -81.9   260.5   23  60.00  1... ...
  -138    -65    202    0    -1   -198.8   -56.4   255.1   -62.6   23  60.00  1... ...
   155   -196     42   -0     1    179.5  -262.3    82.7  -260.7   23  60.00  1... ...
```

Figure 5. Sample oscillographic event report in ASCII format

Considerations for COMTRADE Use

The IED sampling rate impacts the resolution and the amount of data within an event report. Advanced analysis software, such as that shown in Figure 6, provides valuable harmonic and modal evaluation capability, but these analyses only apply to event reports using higher sampling rates. The sampling rate can vary anywhere from 4 to 128 samples per electrical cycle. The length of recording depends on the source device and its configuration. Many software applications, including some that are free, can open and graphically display oscillographic event reports to assist in root-cause analysis, as shown in Figure 6.[5] The data in each of the samples shown in Figure 5 do not have an individual time stamp; the time for each sample is derived from the event trigger time, sampling rate, and offset.

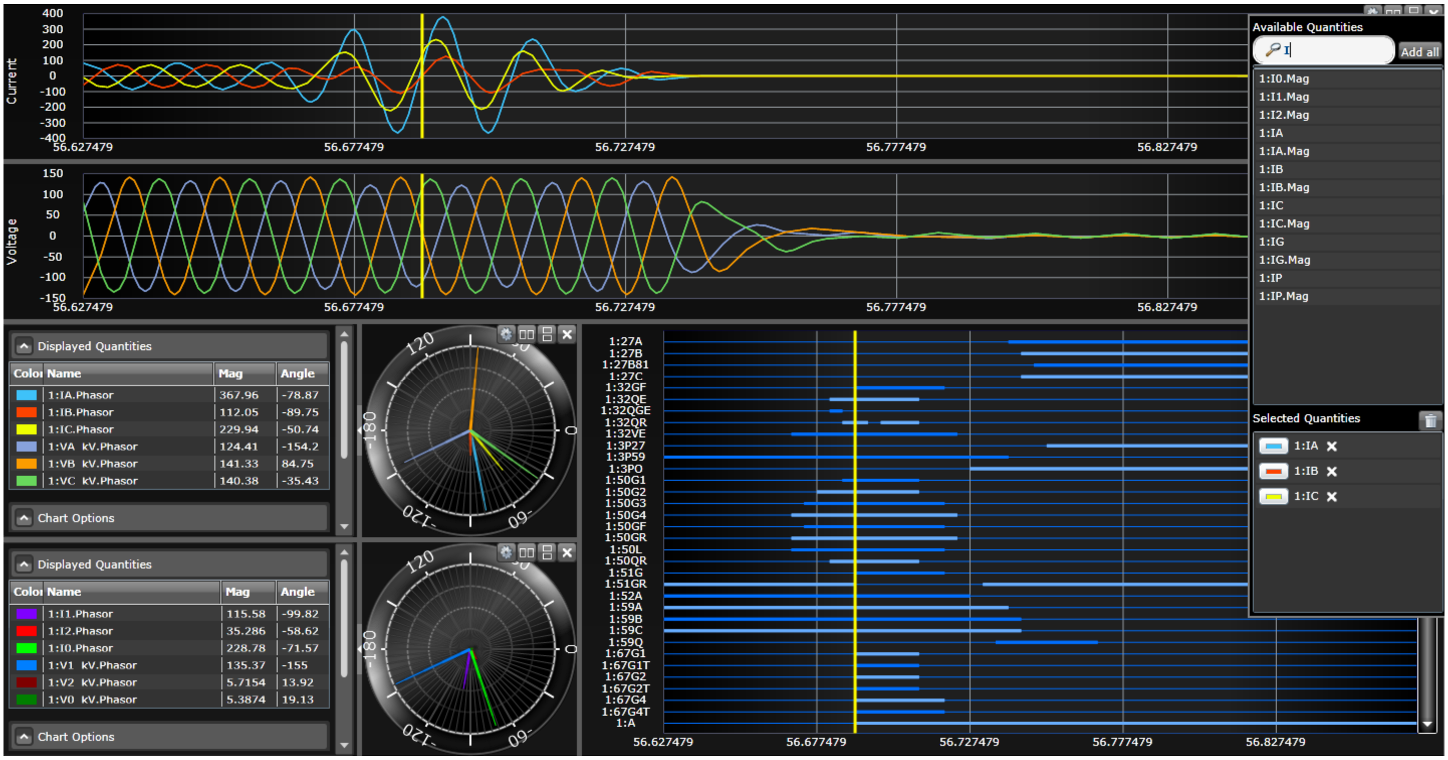
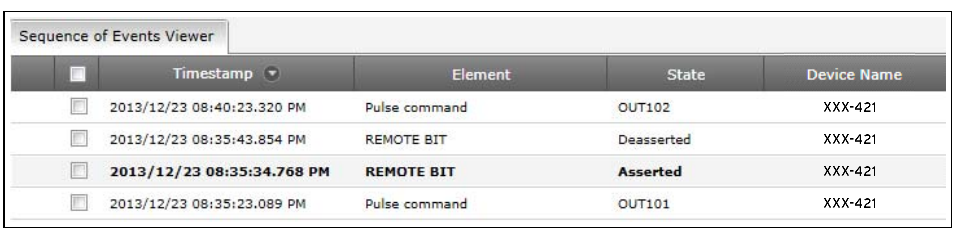


Figure 6. Oscillographic event report

Along with triggered oscillographic records, IEDs also keep ongoing time-sequenced records of state changes called sequence of events (SOE) or Sequential Events Recorder (SER) reports. These SOE records are state changes time-stamped to the millisecond. Some methods exist to move SOE data into control systems via SCADA-type protocols like Modbus® TCP or IEC 61850. Sample SOE data are shown in Figure 7.



Sequence of Events Viewer

Timestamp	Element	State	Device Name
2013/12/23 08:40:23.320 PM	Pulse command	OUT102	XXX-421
2013/12/23 08:35:43.854 PM	REMOTE BIT	Deasserted	XXX-421
2013/12/23 08:35:34.768 PM	**REMOTE BIT**	**Asserted**	XXX-421
2013/12/23 08:35:23.089 PM	Pulse command	OUT101	XXX-421

Figure 7. SOE data

Combining oscillographic event reports with SOE data gives a complete picture for analyzing the system after a disturbance. Electrical staff need to gather these reports from many devices into one location to enable convenient access, analysis, and archiving.[6] Traditional manual methods of gathering these records are time-consuming and expensive and can result in a loss of critical information.

Report Retrieval and Storage

Power system information management software automates the process of recognizing and collecting oscillographic event reports and SOE data from devices throughout a large power system. Once configured, the software either polls the IEDs at a user-specified time interval or, in more advanced systems, waits for notification of events from remote IEDs. The collected data are displayed on analysis screens that support detailed evaluation of oscillographic data. It is important to note that IEDs in a large system located over different geographical regions need to be time-synchronized for accurate analysis. This feature is extremely useful when analyzing and coordinating oscillographic reports from different IEDs within the same plant. Time coherence becomes even more critical for events generated over wide geographic regions. One popular method for time synchronization is the direct connection of IEDs with Global Positioning System (GPS) clocks using the IRIG-B protocol. The GPS satellite system ensures highly accurate time synchronization, regardless of location.

The integration of process historian data with SCADA data and information from all the IEDs (oscillographic and SOE reports) provides a vital link between the electrical and processing systems within mills in order to facilitate engineering analysis and optimization of plant energy usage. This information can help identify trends over a period of time, ensure quality control, document energy consumption, calculate downtime losses, correlate with other process variables, and improve overall plant productivity and efficiency.

INTRODUCTION TO PROCESS HISTORIANS

A process historian is hardware or a software program that aggregates time-series data.[7] Historians can record manufacturing floor data over a specific period of time from various segments of a manufacturing process for analysis. Historians can trend various types of data such that a process owner can use these time-series data in order to maximize process efficiency. Some examples of data types read by historians are as follows:

- Analog readings, such as temperature, pressure, flow rates, levels, and weights.
- Digital readings from valves, limit switches, motors, and discrete level sensors.
- Product information, such as product identifier (ID), batch ID, material ID, and raw material lot ID.
- Quality information, such as process and product limits.
- Alarm information, such as out-of-limits and return-to-normal signals.
- Aggregate data, such as average, standard deviation, and moving average.

Historians are used across many industries and applications, including the following:

- Consumer products, such as food and beverage, automotive, and life sciences.
- Continuous process, such as packaging and material routing.

A traditional process historian system consists of three major components: a data server, an interface node, and a historian repository, as shown in Figure 8. In most systems, there is also a control layer that consists of an industrial controller. The historian contribution is mainly the storage of process event data in a format that is highly recoverable and indexed by time. The historian data are time-series data; therefore, the data are not relational. Time-series repositories in historians provide a tag name, value, time stamp, and status for each monitored tag. Historian data systems are highly scalable;[7 8] users can add tags and repositories as needs change. Typically, the event time stamp for each record is applied by the interface node. Interface nodes collect, interrogate, and qualify information provided by the data server.[9] If the data values collected at the interface node exceed predefined dead-band thresholds, the interface node applies a time stamp and the data are transferred to the historian repository. If the data do not exceed the threshold, the tag record is disregarded and not archived. This process is better known as exception testing.[7 8]

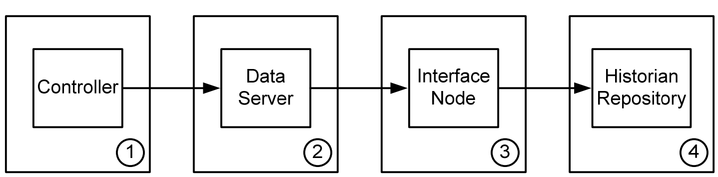


Figure 8. Historian model

The overall historian architecture is shown in Figure 9. This figure shows that DCSs, programmable logic controllers (PLCs), and controllers feed interface nodes within the system. The data provided by these systems are qualified by the interface nodes and passed to a historian server. The historian server can communicate with various analytical tools and other systems, such as maintenance management systems, to run models and generate reports. Finally, various clients, whether local or remote, can access the data from the historian server within the enterprise network.

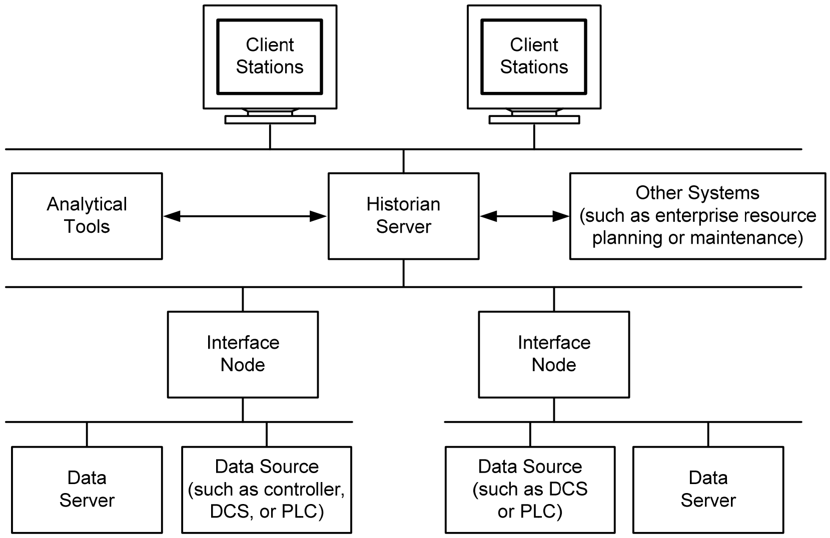


Figure 9. Historian architecture

INTEGRATING RELAY EVENTS IN PROCESS HISTORIANS

A process historian provides visibility into the behavior of the processes and infrastructure of an enterprise. The addition of power system events and granular data surrounding a significant event, such as a tripped feeder, supports system analysis for maintenance. The time-series storage mechanism supports reporting based on the time of events for both power systems and processes. This is why process historians are commonly used by mill operating and maintenance personnel to collect events from as many process domains as possible, such as the power system and manufacturing, to provide the event infrastructure for an enterprise.

System Components and Connections

The movement of oscillographic event data from an IED to a process historian requires, from a high level, some integration of the technologies that are in each layer of the system. Figure 10 shows an overview of the components that compose a system that supports the archiving of oscillographic event data into a process historian. The digital status of an event, commonly called an SOE report, can be gathered in several ways: by using DNP3, IEC 61850, or a database that contains the actual event time and duration. This paper is focused on the associated data that surround the digital event.

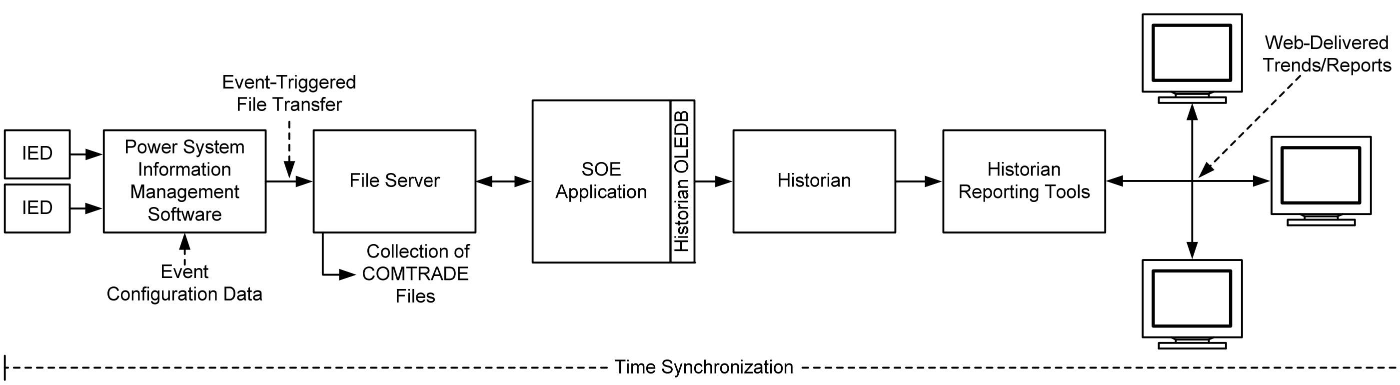


Figure 10. System overview

All of the components of the integrated historian system depicted in Figure 10 need to be time-synchronized such that subsequent reports including data from many different plant sources do not have time coherency and alignment errors. For example, if there is a system such as that shown in Figure 8, which typically employs a 1-minute poll rate, that is later integrated with power system events that are accurate to 1 millisecond, users will want to be assured that both time-stamping systems are synchronized to the same time reference and to the smallest unit of time. This uniform time synchronization supports getting to the root cause of events and comparing process variables with power system events. When comparing events, it is important to know the data collection technique used.

For explanation purposes, the overall system shown in Figure 10 is discussed as two subsystems: the collection of oscillographic data and the organization and storage of the data in a process historian. Note that the two subsystems are independent and have their individual areas of responsibility. The file generation and management subsystem is responsible for gathering the IED event data and storing the data in a standard COMTRADE file format. On the other hand, the historian subsystem is concerned with the collection and presentation of the event data and the surrounding data that can complete the analysis.

File Generation and Management Subsystem

The file generation and management subsystem, as shown in Figure 11, consists of three components: IEDs, the power system information management software, and the file server. Typically, the power system information management software resides on the file server; for discussion, these two components are separated.

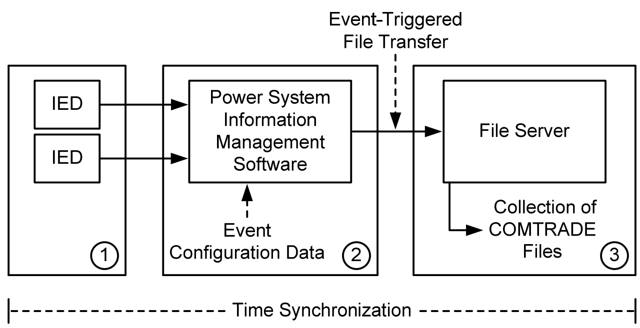


Figure 11. Event file generation and management

The subsystem depicted in Figure 11 has the following components:

1. IEDs. These can include many microprocessor-based protective relays, power meters, and equipment monitors located throughout a facility. Based on the application, designers configure each IED to record SOE and oscillographic reports based on predetermined criteria. The reporting configuration includes identification of analog channels, digital channels, sampling rates, and report duration.
2. Power system information management software. This software application runs as a continuous operating system service and contains configuration information regarding network connectivity to each IED and how it should collect event reports from each device. When the software recognizes a new report in a monitored IED, it submits the report to the file server for storage. Some power system information management software also converts manufacturer-specific event reports into COMTRADE format. New implementations of power system information management software include the ability to also receive and archive a high-speed, continuous stream of time-aligned power system phasor data in addition to COMTRADE event reports.
3. File server. This is the final location of the oscillographic data in the form of a COMTRADE file. The file, once processed, is moved to a completed folder. Some consideration must be given to manage the files that are processed. For example, these files should be backed up and removed from the server to ensure that there is enough free space for future COMTRADE files. This is also a good process variable to be logged into the historian for reporting that the file server may be full.

Because the storage of the oscillographic data can be based on electrical cycles prior to and after an event, the IED must buffer the signals continuously such that when an event occurs, the IED can take the data from the buffer and produce the three files described previously, namely the CFG configuration file, the HDR header file, and the DAT data file.

When the files are created, they are stored on the IED. These files are then transferred to the file server by the power system information management software. The power system information management software is a middle-tier application that marshals the data from the IED to the file server. This is shown in Box 2 of Figure 11. The power system information management software manages the transfer of the oscillographic event report data from the device to the file server shown in Box 3 of Figure 11. The event configuration data shown in Box 2 of Figure 11 represent the power system information management software configuration for connecting with and retrieving reports from an IED.

When the power system information management software transfers oscillographic or SOE data to the file server, the files are placed in a central folder. The COMTRADE filename includes device identification information that is used by the process historian system in order to determine how tags should be applied in the historian.

Process Historian Subsystem

Figure 12 shows the process historian subsystem.

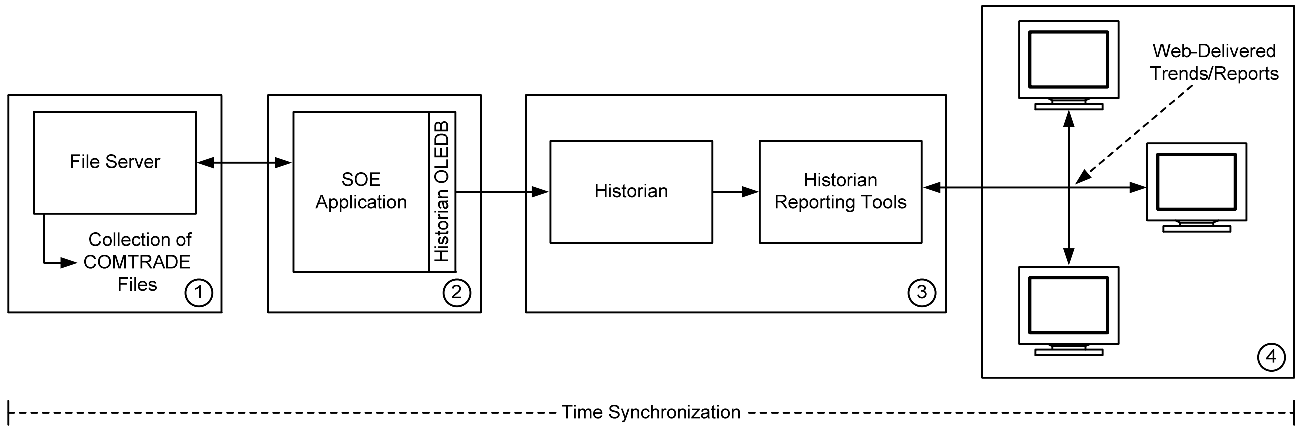


Figure 12. Oscillographic file consumption

The SOE application in Box 2 of Figure 12 uses a folder watch mechanism to monitor the file server for new COMTRADE files to begin processing. This application processes the oscillographic data and inserts them into the historian. Finally, it moves the files from the source folder to a processed folder.

The SOE application processes the data on demand, meaning that when a file arrives, it is read and formatted for insertion into the historian. After the data are placed in the historian, the application waits for another file to arrive in the folder. When the file is processed, the SOE application creates individual data record time stamps by using the trigger time and the offset stored in the COMTRADE file. This means that the IED is in control of the time stamp applied to the event data. So, if the file remains in the IED or file server for an extended period prior to processing, the SOE application will still be able to apply the correct time stamps in the historian. This attribute also ensures that there is no loss of data as long as the file is intact. Potential users may be concerned that COMTRADE data may have a processing delay prior to availability in the historian. However, this should not be an issue, practically speaking, because the primary use of the data is root-cause analysis for faults, which typically occurs some time after the event.

Once the oscillographic data are in the historian, trending and calculations can be performed for reporting purposes.

CONCLUSIONS

Adding relay oscillographic reports into process historian repositories provides mill maintenance and operations personnel with important information concerning the root cause of electrical system faults and enables new and powerful methods to evaluate mill operations in context with as many process variables as possible. The solution described in this paper employs commercially available power system information management software to retrieve and store COMTRADE event reports from IEDs throughout a mill electrical system. Software tools within the process historian watch for new reports in the power system information management software and parse the COMTRADE reports in order to include these data within historian repositories. Users then have access to IED event information within all of the reporting and analysis tools at their disposal.

Because energy usage, especially electricity, is such a large component of product manufacturing cost, mill operations personnel need this type of information to optimize the energy delivery system within the plant. The combination of modern IEDs and powerful reporting tools allows these personnel to find creative ways of improving mill performance.

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