# Intelligent Design

Substation Data Integration for Enhanced Asset Management Opportunities

By Mladen Kezunovic

THIS ARTICLE EXPLORES A NONTRADITIONAL approach to asset management in which operational and nonoperational data captured during power system events like faults and other disturbances are utilized for condition-based assessment of power system assets such as transmission lines, circuit breakers, and transformers. As an example, during faults on transmission lines, determining the location of the fault and the condition of circuit breakers is critical to managing transmission line repair and restoration. To manage the assets in this case, it is necessary to obtain field-recorded data from substation intelligent electronic devices (IEDs). Substation IED data may be combined with the traditional (historical) asset management data to draw immediate conclusions about the asset's condition and its availability for continued use after it has been stressed due to a random event. The topic of the use of condition-based data to enhance asset management opportunities is a complex one that requires an explanation of how condition-based data may be converted to information leading to knowledge useful for decision making. In this article, we explore the implementation issues of such a concept, leaving it to the reader to become familiar with the fundamental issues of the use of condition-based data in asset management through literature offered for further reading.

Data Integration and Information Exchange

The first step in developing future substation automation systems capable of producing improved information leading
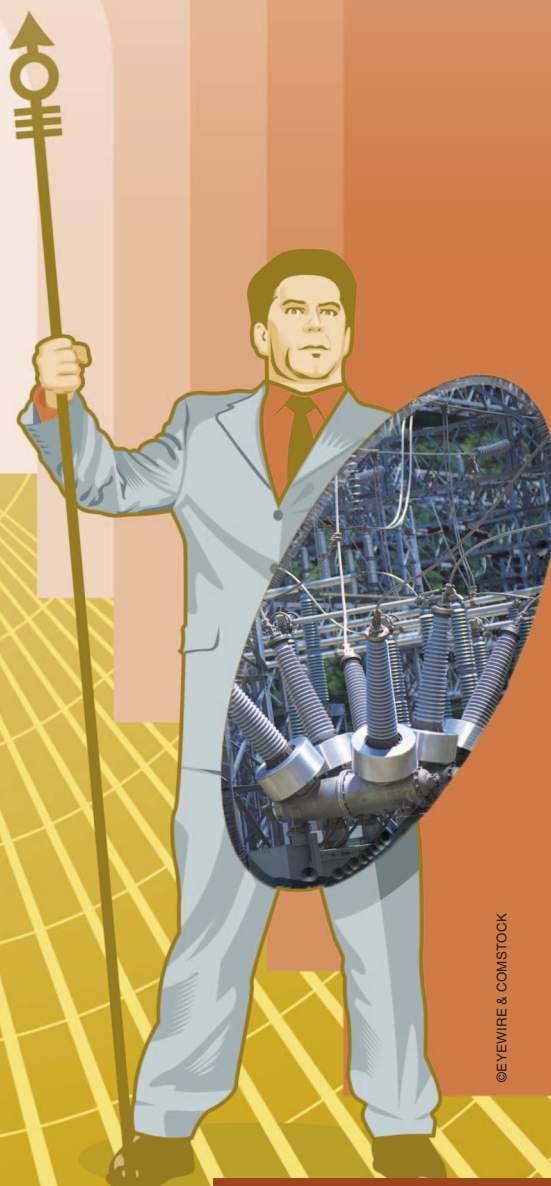
to the knowledge needed for decision making is to integrate data from multiple substation IEDs and extract information that may be of interest to different utility groups: protection, operations, and maintenance. This concept is shown in Figure 1. Data from individual substation IEDs such as fault locators (FLs), digital fault recorders (DFRs), circuit breaker recorders (CBRs), digital protective relays (DPRs), phasor measurement units (PMUs), remote terminal units (RTUs), and sequence of event recorders (SERs) already provide useful information associated with stand-alone IED data capture. The traditional approach to using such data is to provide it to certain utility groups via dedicated infrastructures, as illustrated in Figure 1: FL data may be collected through a centralized fault location (CFL) system; DFR data may be combined through local master stations (LMSs) and collected at the master station (MS); DPR data may be brought to the protection engineer (PE) interface; and RTU and SER data may be collected by the substation center (SC) and the regional center (RC) for the use of the energy management system (EMS).

An alternative (shown in red in Figure 1) is to combine the data recorded by the individual devices using an integrated system (IS) to provide a more relevant and versatile source of information to serve asset management applications such as fault location and transmission line restoration, circuit breaker monitoring and maintenance, alarm processing and diagnostics, and so on. The IS that interfaces with each IED makes those data accessible to the applications located in the control center or engineering office. The data integration and information exchange, when combined with traditional asset management historical data and power system component models, provide a powerful tool for substation- and system-level asset management. In this concept, every substation IED supplies each utility group with data and, subsequently, information

of interest to that selected group. As an example, the asset management group may use fault location data computed by protective relays or DFRs to enhance decision making about the transmission line repair and restoration after the occurrence of a fault. Similarly, the circuit breaker condition-based data coming from circuit breaker recorders, protective relays, and DFRs may be utilized for better circuit breaker condition assessment and maintenance strategies. The alarm processor may be used to detect abnormalities in the power apparatus operation, which may be based on alarms captured by multiple IEDs.

System Architecture

The proposed concept of data integration and information exchange at the substation level may be extended to the overall system level. Figure 2 shows a simplified example of the system architecture for integration of operational (supervisory control and data acquisition, or SCADA) and nonoperational (DFR, DPR, and CBR) data. Data are collected from IEDs in the COMTRADE file format, processed at the substation level, and populated into the database together with the automated analysis reports and recording system configuration information. Integrated IED data and analysis reports can be accessed and visually inspected using individual graphical user interfaces (GUIs) that display results from each of the automated analysis applications, which are the core of the information and knowledge conversion needed for decision making. The changes in the database containing integrated and processed IED data are monitored by a control center adapter that merges those data with SCADA data and translates SCADA and IED data into the Common Information Model (CIM) data format. The analysis and processing applications at the control center or asset management center level—in this example, optimal fault location and intelligent alarm processing—use the data in translated in CIM format for further processing.

The automated event analysis (AEA) client software is installed on the substation PC and performs only data acquisition from all IEDs. The AEA server installed in the centralized location performs automated functions such as converting data formats, classifying events, renaming IED data from substations, interfacing with custom analysis applications, and allowing immediate processing of acquired data, as well as uploading raw and processed IED data into the IED database. In this example, three types of the automated analysis applications are considered: CBR analysis (CBRA), DPR analysis (DPRA), and DFR analysis
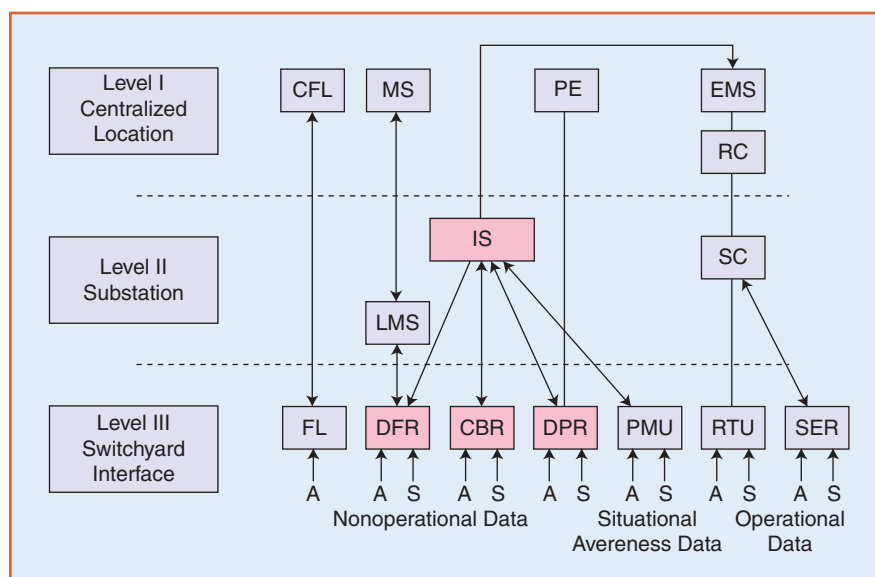
figure 1. Concept of data integration and information exchange.
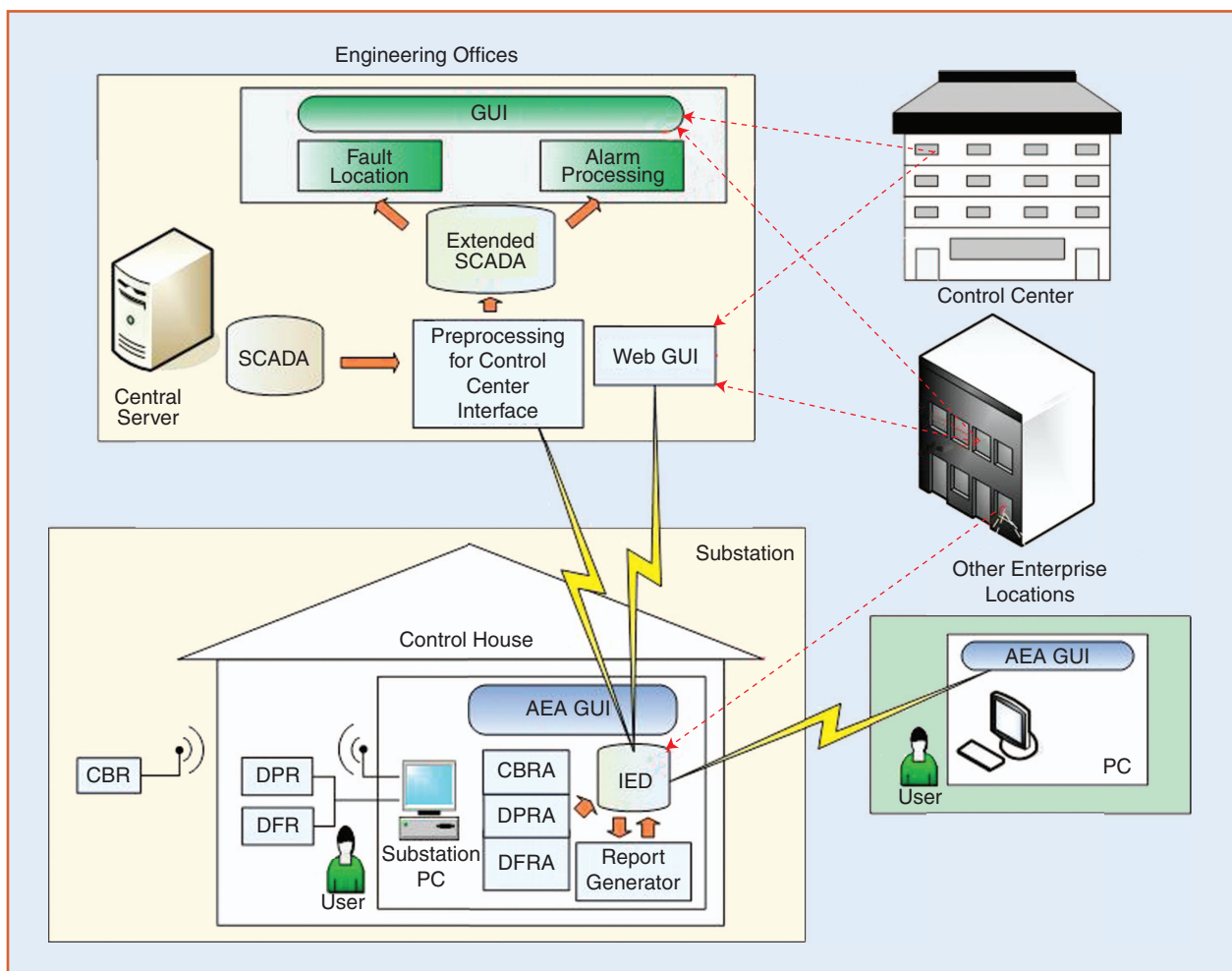
figure 2. Implementing the data integration and information exchange concept.

(DFRA). As shown, multiple user interfaces are possible: a local AEA GUI for substation engineers, an engineering office interface for enterprisewide engineering support such as asset management, and situational awareness interfaces for system operators located in the control center.

Fault and Disturbance Analysis: An Example

An implementation scenario of substation automated analysis software is depicted in Figure 3. Substation IED data such as event records from DFRs, DPRs, and other types of IEDs are automatically collected and made available to the users.

The solution consists of the following elements:
- ✔ a processing and analysis client
- ✔ a data manager
- ✔ a substation data mart (data warehouse) server
- ✔ a user interface.

The processing and analysis client collects the IED records and automatically converts them into a unified, nonproprietary file format. Signal waveforms—namely, voltages and currents—are mapped to monitored power system compo-

nents (transmission lines, circuit breakers, and transformers). The processing includes fault type detection, disturbance classification, and single-end fault location calculation. The processing and analysis software module for each IED type group (DFR, DPR, CBR, and so on) typically corresponds to the IED-level functionalities mentioned previously.

The data manager is responsible for broadcasting reports and maintaining the data warehouse and centralized data repository. In addition, it provides functions for broadcasting notification to selected users via e-mail and/or pager service. Optionally, the two-end fault location function can be attached to the data manager. The fault location module demonstrated later in the article utilizes phasor-based two-end fault location calculation. Every time the data manager receives a new event file from one end of the line, it checks the data warehouse for an event file from the remote end that falls into a predefined time frame. If such a file is located, the two-end calculation is executed.

All the converted event data, analysis reports, and system configurations are kept in the data warehouse. The data warehouse server utilizes a standard database engine and a centralized file repository. Keeping the event data

in a standard, nonproprietary file format enables direct access and use of fault data even with standard file managers such as Windows Explorer. The database implementation utilizes standard database interfaces such as the SQL subset that work with most database engines.

The main user interface is Web based and lets users access the data warehouse utilizing a standard Web browser such as Internet Explorer or Firefox. The interface is realized using standard HTML/CSS technology. For more elaborate user interfaces (including non-Web-based ones), there are variety of technologies available. For example, one of the latest Java technologies, Web Start, can be used for implementing the waveform and report viewer that runs as a desktop application on a client computer but starts via a Web server and does not need to be installed locally on the user's computer.

Application Scenario

An example of a monitored transmission line is given in Figure 4. Multiple IED types are used in a substation in this example: a DFR that monitors all the transmission lines,

transformers, and buses; DPRs (primary and backup) at each end of transmission line; and CBRs monitoring the control circuits of the main and middle breaker of each transmission line configured in a breaker-and-half bus arrangement. Several IEDs may be triggered to capture the same event. In this example, it is assumed that a fault will trigger recording at all IEDs connected to the monitored line, which in turn results in five records at this substation that correspond to the same fault. It is also possible that not all the IEDs will capture the event, so that four, three, or fewer event files would be available in case one of the relays or breakers did not operate. Figure 4 considers event records obtained only in one substation. A similar number of event records would come from the substation at the remote end of the transmission line, and there might be some records captured in the neighboring substations (at the least, DFR or DPR files). As a result, one fault can easily result in a dozen or more IED records. Manual processing of all this information can be cumbersome, especially if one takes into account the fact that the IEDs can be from different vendors and vintages. Such a case requires different versions of the data-collecting and data-viewing software.

Dealing with data coming from variety of IEDs from different vendors typically implies the use of vendor-specific data communication and collection software. It is not uncommon that a single vendor may have multiple software packages for different equipment vintages. In most cases it is possible to configure IEDs for automated data retrieval and to assume that within a certain time frame all newly recorded event files will be downloaded and available on a file server on a corporate network. North American Electric Reliability Corporation (NERC) requirements for handling substation disturbance data as well as for cyber security should be consulted for implementation of IED communication and data collection. All substation event data should be properly time-stamped using a Global Positioning System (GPS) clock with absolute time reference so that all of the event records can be sorted in historical order as well as grouped into clusters of event files that correspond to a single event.

A very good choice is to make a "clean cut" between data collection,
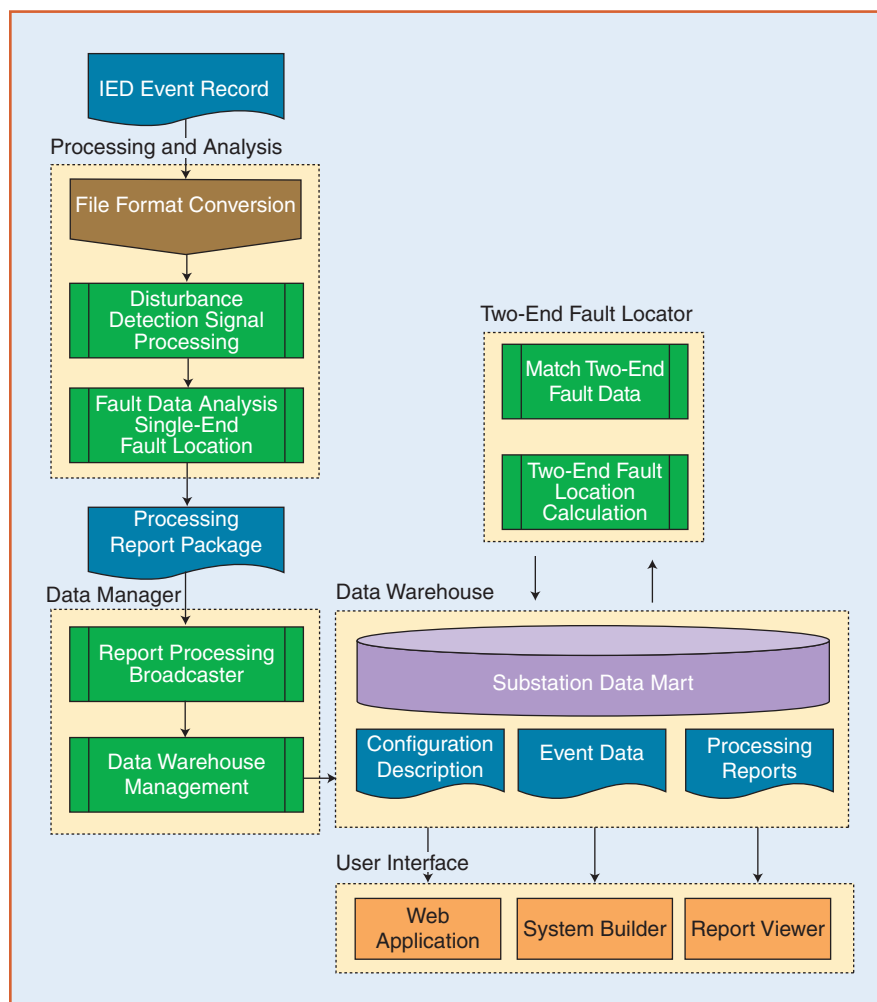
figure 3. Example architecture for substation automated analysis software.

data conversion, and data processing so as to avoid combining the different pieces of the solution "puzzle." Automated data processing and analysis functions should be decoupled from the data integration, if possible. The following sections discuss examples of fault location and circuit-breaker-monitoring applications.

Integrating Fault Location Data for Transmission Line Repair and Restoration

This discussion illustrates how condition-based data collected in the field during a fault may be used to make decisions about transmission line repair and restoration. During the fault, various IEDs, such as FLs, DFRs, and DRPs, may produce fault location information; such information is critical to an efficient and timely repair of the transmission line damage before restoration. Several examples explore a practical problem: the case in which multiple IEDs calculate fault location on the same transmission line but the results are different due to different qualities and uses of field-recorded data. The problem is illustrated by showing results of single- and two-end fault location algorithm implemented using DFR and DPR data. The first example shows how the DFR data may produce different fault location results depending on whether it is available at one or both ends of a transmission line. The second example illustrates how different types of data may be used to obtain very similar results (using DPR instead of DFR data). In both cases, the user interfaces presenting the results and allowing various comparisons and evaluations of the results are shown. In this implementation, a product called Software Assistant is used to obtain and view the results. The importance of the examples is to illustrate options for obtaining fault location data, which in turn can be used to enhance the asset management analysis of transmission line restoration after faults.

In this field-implementation example, around 50 DFRs are sparsely installed throughout the utility system. This means that it is not a common situation to get DFR data from two adjacent ends of the same transmission line due to the limited number of DFRs used in the system. Around 33,000 DFR records were available and used for in-house evaluation of the fault location application. The files were copied in their native DFR file format, automatically converted to COMTRADE, and processed and analyzed to identify disturbance and fault type, evaluate system protection operation, and calculate distance to the fault. The calculated fault location was compared when feasible with the historical data, which unfortunately were not available for most cases. In some instances, the data from both ends of the line were available, so a comparison between single- and two-end fault locations took place. An example of such comparison is given in Table 1. The Web interface for accessing integrated substation IED data is customized to allow easy access and overview of the results, as shown in Figure 5.
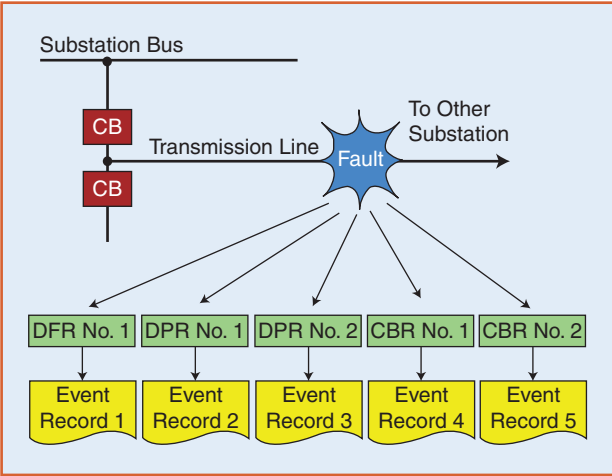
figure 4. Monitored transmission line: several event records captured for a single fault.

table 1. Event location example, using DFR data.			
Event Description		**Substation Assistant Analysis**	
Event Time	**Substation**	**Single-End Location**	**Two-End Location**
2007-03-14 18:34:39.169	Bus A	6.4 mi	6.7 mi
	Bus B	4.1 mi	4.6 mi
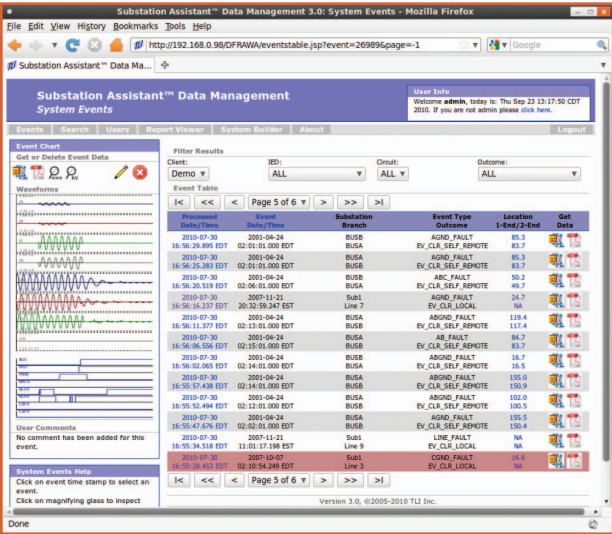
figure 5. Browsing IED (DFR/DPR) data via the Web interface.

In addition to DFR data, manually collected files from ten Schweitzer Engineering Laboratories (SEL) and General Electric (GE) DPRs are used. Two-end data were available in this case, since the same pairs of relays are used at both ends as primary and backup protection. Several DPR data files have been processed and analyzed. Since DPRs typically provide both oscillography and fault reports, the fault location data may either be extracted by parsing the

table 2. Event location examples for protective relay data.				
		Substation Assistant Analysis		**SEL Relay Reports**
Event Time	**Substation/Bus**	**Single-End Location**	**Two-End Location**	**Single-End Location**
2008-05-14 04:40:38.48	Bus A	8.7 mi	8.2 mi	8.75 mi
	Bus B	0.3	0.2	0.16
2008-05-14 04:09:02.45	Bus A	8.4	8.6	8.61
	Bus B	0.1	−0.2	0.05
2008-05-14 02:49:59.83	Bus A	8.4	8.6	8.63
	Bus B	0.0	−0.2	0.05

the main challenge is to automate auto-poll (or auto-call) for obtaining IED event data automatically. With Ethernet and auto-call, there is the possibility of dramatically reducing the time from the capture of an event record to the moment processed data and a report show up in the database.

An interesting benefit surfaced from another setup in which both DFR and DPR data were available. An event captured by both relays and fault recorders resulted in detection of "bad data" associated with a DFR record. An obvious B-G fault was identified as C-G, and all the calculated values were incorrect. Quick manual analysis of the DFR prefault data and comparison with the files obtained from primary and backup relays indicated that the B-phase wiring was incorrectly inverted, thus resulting in a 180° shift, as shown in Figure 7. The angle difference in the prefault should be 120°, not −60. What made this harder to spot, for this particular line, was that only phases A, B, and N were monitored. Having both relay and DFR data integrated into the same repository and easily accessible with the universal event viewer helped confirm the wiring problem quickly. This example also prompted a review of the monitoring policy, to check it against NERC recommendations.

reports or calculated based on the oscillography data. For practical use, it is important to know whether the oscillography data have been filtered or unfiltered and to try to obtain DPR data with the highest available sampling rate. An example of fault location obtained from oscillography data or using the calculated data from DPRs is given in Table 2. The table compares single-end calculation, two-end calculation, and calculated FL values parsed from digital relay reports. It is important to note that the two-end data obtained from SEL relays in these cases show very good alignment due to the use of a GPS-synchronized clock available at both end of the transmission line. The time difference for event trigger was under 10 ms. The highest available sampling rate was used, and a very good match between calculated values and SEL reports can be observed. The universal report and event viewer is used to enable easy inspection and manual analysis of IED records regardless of IED type (DFR, DPR, CBR, and so forth). Special attention is needed when dealing with low-sample-rate data, as in the case of some of the relay data shown in Figure 6.

The typical processing time for an event file (DFR or DPR) was less than 1 s. From a deployment perspective,

Integrating Circuit Breaker Recorder Data for Diagnostics and Maintenance

This section discusses adding circuit breaker recording functionality to an existing DFR and DPR setup. For this purpose, a new device called a CBR has been developed and deployed in a substation.

The concept is to provide continuous monitoring and event-based recording for open/close events by
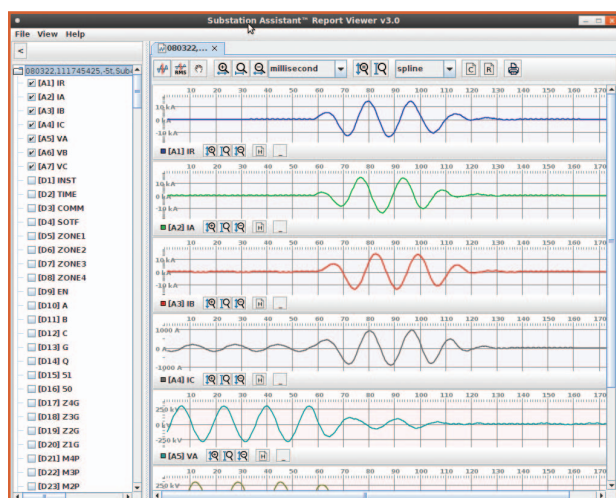
**figure 6.** Opening SEL files with the universal event viewer.
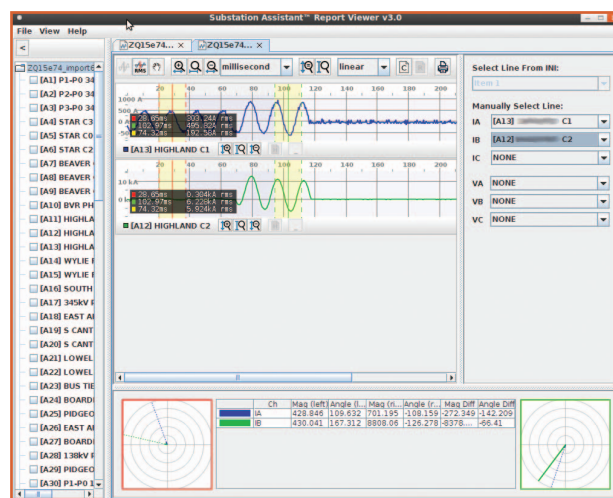
figure 7. Identifying incorrect wiring (B-phase).

connecting to the control circuit of a circuit breaker. Table 3 shows input signals of interest for the circuit breaker monitoring.

It is necessary to provide a sufficient set of monitoring points inside the control circuit of the breaker in order to provide an insight into the operation as well as the condition of the breaker. Trip/close coil currents, phase currents, a/b contacts, and X/Y coil signals allow taking a snapshot of the health of the breaker every time it operates, as shown in Figure 8. The field installation setup is depicted in Figure 9.

In this example, the communication inside the switchyard was implemented via wireless frequency-hopping

| table 3. CBR input signals.	
Open Operation	**Close Operation**
Trip coil current	Close coil current
Supply dc voltage	Supply dc voltage
Yard dc voltage	Yard dc voltage
Backup dc	Backup dc
A contact	A contact
B contact	B contact
Phase currents (ABC)	Phase currents (ABC)
	X coil
	Y coil
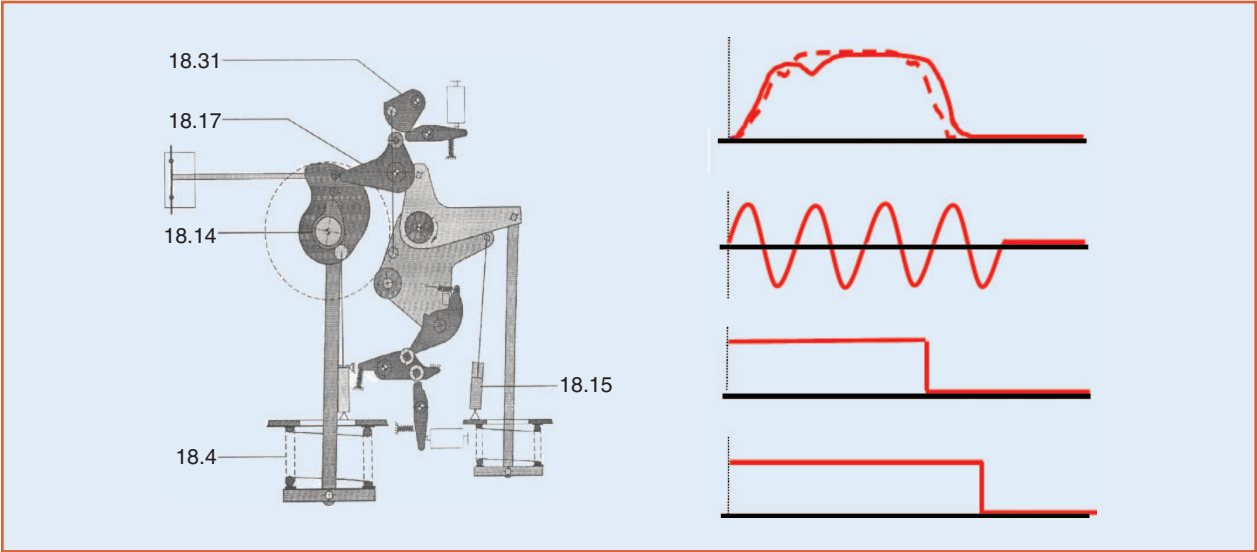
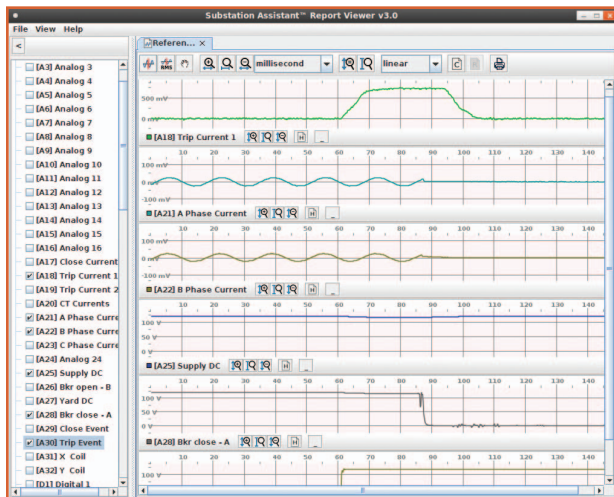**figure 8.** Electric signals mapped to the mechanical condition of a circuit breaker.
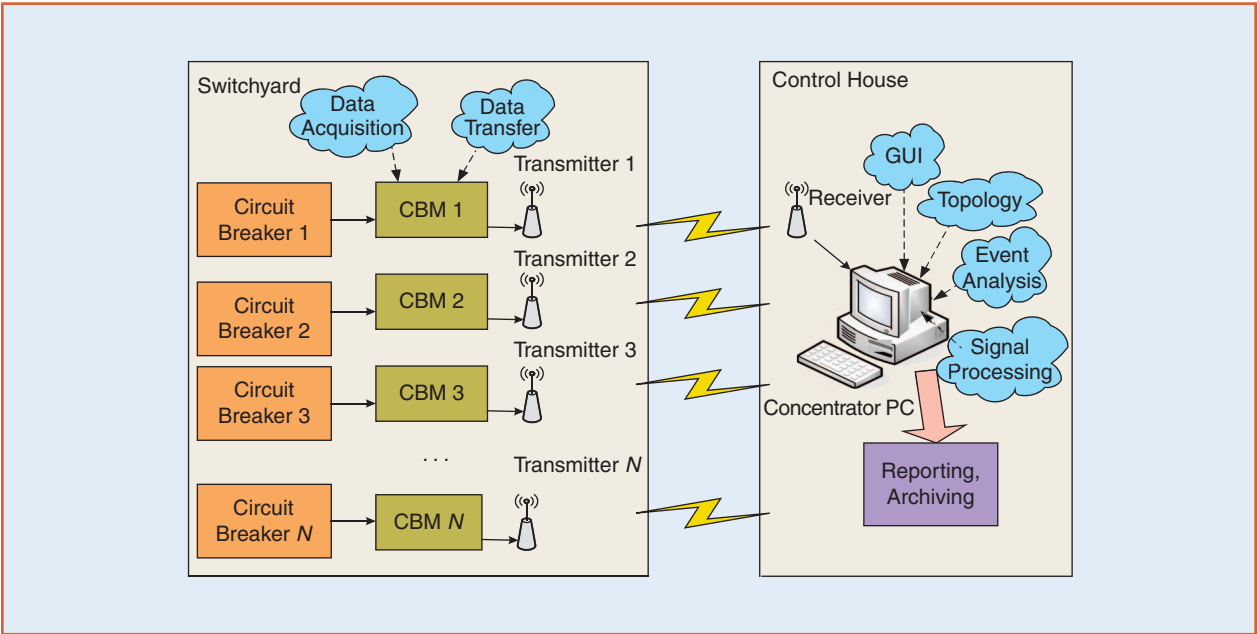
figure 9. Circuit breaker monitoring setup.
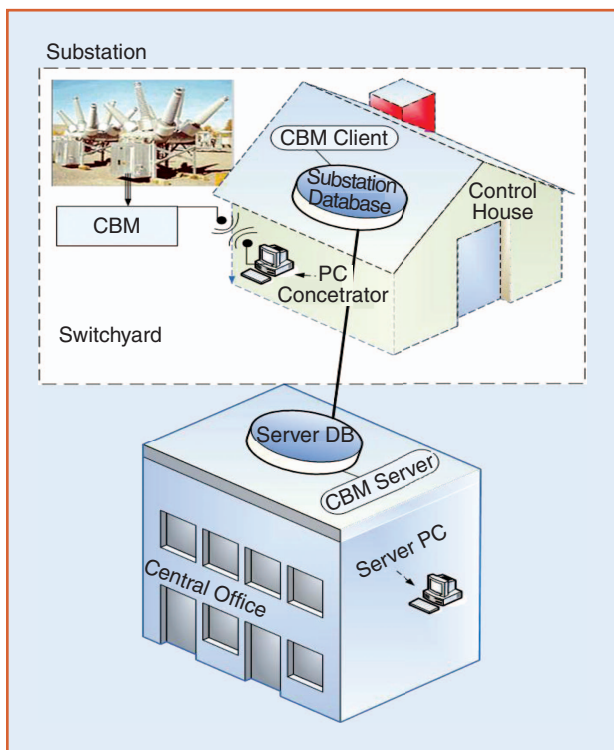
figure 10. Implementation architecture for condition-based monitoring of circuit breakers.

figure 11. Inspecting circuit breaker control circuit signals.

spread-spectrum modems. The distances between the control room and the closest and furthest bus were 250 ft and 600 ft, respectively. The evaluation of wireless channels was performed in the field by having the new device next to the circuit breaker control cabinet while the computer with the master modem was inside the control room.. An additional challenge for the evaluation was the fact that the control room resides behind a large power transformer.

The communication testing went without much trouble. If needed, the master modem can be mounted outside, above any obstacles, in a direct line of sight with the monitored breakers. Since the CBRs do not have any control function but only a monitoring function, they have been identified as "noncritical" assets for the purposes of NERC's cyber security recommendations.

The final implementation is shown in Figure 10. The records from the control circuit are collected each time a breaker operates. A good approach is to keep a set of good reference cases that can be used as a baseline for evaluation of the open/close operation of the breaker in question. It is critical to understand both the signal levels and, even more, the signal timings as they directly correspond to the condition of the breaker. The features to look at include trapezoidal trip/close coil current shape, phase currents on/off, "a" and "b" contacts, and voltage dip in dc supply.

For the most part, the analysis can be done by visually inspecting the signals. A very useful tool is overlaying the record with corresponding reference cases. In addition, for this particular setup a set of automated processing and analysis functions has been implemented to provide automated calculations and reporting of all the timings and changes in a tabular form. Figure 11 depicts an example of trip coil current, one of the phase currents, a dip in the dc supply, and "b" and "a" contacts.

Having all of the CBR records in a centralized repository allows for implementation of the breaker "health assessment" function and enables better forecasting of possible failure. This facilitates risk assessment of breaker operations and eventual maintenance scheduling. The historical data with records from all open/close breaker operations become a powerful tool in the hands of maintenance and asset management groups, as they let them make better-informed decisions about preventive and corrective maintenance.

For Further Reading

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Biography

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