Automation of Fault Analysis: Implementation Approaches and Related Benefits

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Abstract

Automation of fault analysis is a desirable future application due to "explosion" of on-line substation data collected during disturbances. Analyzing this data manually is just not feasible; automation of the analysis is necessary. This paper focuses on three options for implementation of automated fault analysis based on: a) uses of individual Intelligent Electronic Devices such as Digital Fault Recorders (DFRs), Digital Protective Relays (DPRs), Sequence of Events Recorders(SERs), etc, b) integrated substation automation systems with all Intelligent Electronic Devices (IEDs) interconnected, and c) integrated enterprise monitoring and control system including Supervisory Control and Data Acquisition (SCADA) Remote terminal units (RTUs) combined with other substation IEDs. For each of the approaches, implementation requirements are discussed and possible benefits are outlined.

Keywords

Fault Analysis, Intelligent Electronic devices, Automated monitoring, Substation Automation

1. INTRODUCTION

Fault analysis is an important function in performing power system monitoring. It assures that all the faults are correctly identified and analyzed, as well as that appropriate restoration actions are taken in the shortest possible time. To achieve this goal, fault analysis has to be automated. This encompasses automated collection, processing and displaying of data and related analysis reports. Since many implementations for automated fault analysis are possible, it remains to be determined which approaches are feasible and what their benefits are [Kezunovic et al, 2000].

This paper illustrates that fault analysis may be done using different combination of IEDs. The choice of IEDs depends on many considerations: maintaining legacy practice, expanding the recording capability, integrating with other data sources across the enterprise. Examples of various options for the implementation are discussed by pointing out various benefits achieved with each solution.

The paper focuses on four issues when discussing each of the options: data collection, analysis functions, displaying options for viewing the results, and related benefits. It is shown that choices of what data is used for the analysis create different analysis capabilities. If only one Intelligent Electronic Device (IED) type is used, the analysis heavily depends on the capabilities of that recording device. If multiple IED types are used, additional redundancy and information are available and can be used to make the analysis more robust. The use of additional data beyond what is available form IEDs, such as SCADA database, satellite data and short circuit programs, further enhances the capability for the analysis, particularly in deterring fault location more accurately.

The paper covers three examples of the implementation and for each example several differences in the data, analysis, user displays and benefits are discussed.

2. USE OF DFR DATA

2.1 Data

Digital fault recorders (DFRs) capture disturbance data such as voltage and currents and contact status for circuit breakers. Different trigger conditions may be used to initiate recording of the disturbance event. Typically, the trigger conditions are set so that DFRs may capture data even in the cases of no fault events. This results in a large number of DFR data files. An example of a setup for automated fault analysis using DFR data is shown in Figure 1 [TLI, 2003].

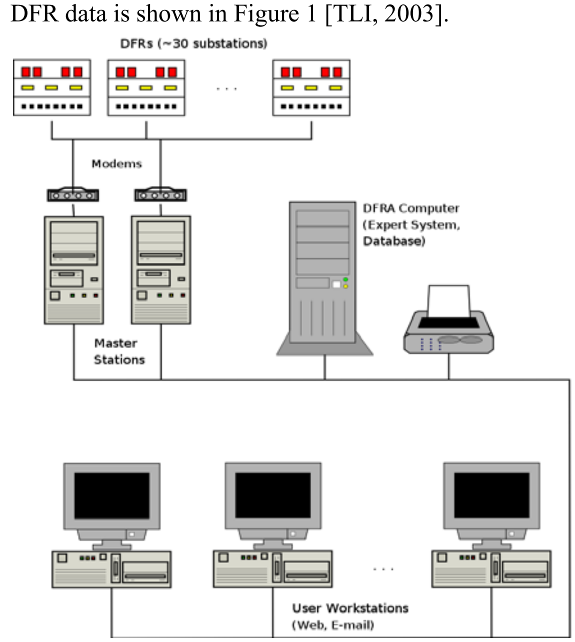

Fig. 1 DFR system for automated fault analysis

DFR master station software is used to automatically retrieve newly recorded data files. The data are typically retrieved using auto-poll or auto-call communication scheme. A file copy routine transfers new DFR recordings to the DFRA computer that hosts software for automated analysis. DFR data is being analyzed and both the data and analysis reports are kept in the centralized database.

There are several requirements that need to be met for implementation of automated fault analysis using DFRs:

- *Automatic retrieval of DFR event recordings*. DFR data based fault analysis is triggered by an occurrence of a new DFR data file. DFR data files should be converted from vendor proprietary data formats into non-proprietary data format such as COMTRADE [IEEE, 1999] to enable integration of DFR data coming from different models, vendors, or even different IED types.
- *Availability of system configuration information*. In addition to DFR recording, the analysis function requires information on how DFRs are configured and description of the power system components being monitored by DFRs. Examples of DFR configurations data are: channel assignments and names, phase information, scaling, mapping to transmission lines, buses, transformers, etc. For the power system components, for example in the case of a transmission line, needed parameters are line impedance, line length, rating, and corresponding.
- *Ability to archive analysis reports*. Output data from the automated analysis functions should be stored into the centralized database.

2.2 Fault Analysis Functions

Main data processing and analysis functions are:

- *Converting data into suitable file formats*. Converting filed-recorded data into non-proprietary data format such as COMTRADE and adopting a file naming convention [IEEE, 2006].
- *Signal processing*. Calculating pre-fault, fault, and post-fault voltage and current levels, finding incidence time and duration of the fault, determining change-of-state times for digital channels, etc.
- *Detecting and classifying faults and disturbances using expert system rules.* Identifying the fault type (A-G, B-G, C-G, AB, BC, AC, AB-G, BC-G, AC-G, ABC, ABC-G) and the type of the event outcome (local clearance, remote clearance, re-closing, unsuccessful re-closing, switching, DFR initialization, etc.)
- *Verifying the system protection operation.* Evaluating the protection relay operation, communication signals, and protection schemes.
- *Verifying circuit breaker operations*. Evaluating the breaker operation and identifying possible breaker problems (breaker failure, breaker slow).
- *Calculating fault location*. Using single-end algorithm when the analysis is performed on one DFR recording at the time. Using two-end algorithm when the recording from both ends of the faulted line are available and is possible to synchronize (align) recorded signals.
- *Determining the priority*. Labeling DFR recordings with the priority flag (high, medium, low) after the analysis is done distinguish between critical and non-critical event data.

2.3 Display

Different options are available for presenting the reports of the fault analysis. Instant notification can be utilized to alert different user groups (pager, email, printer). Event priority flags can be utilized to select which users receive analysis reports. The centralized database is accessible via web application (Figure 2). The events are organized in an event table and the recordings are sorted using the time-stamp. Selecting different events will change signal preview. Web-based COMTRADE viewer allows for manual inspection and fault analysis of the DFR data.

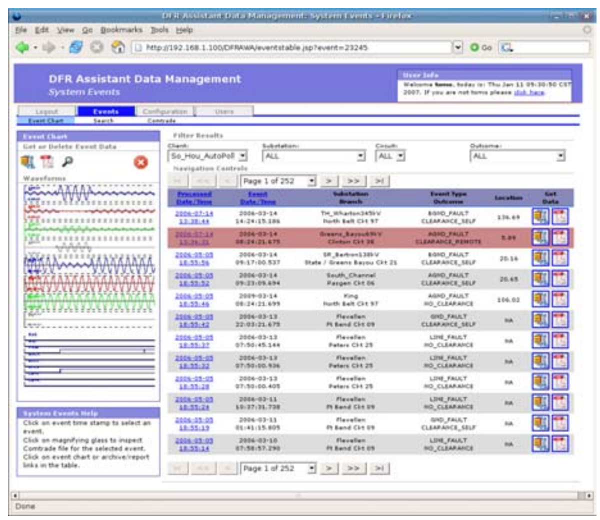

Fig. 2 Using web-based application

D. Benefits

Major benefits of the automated fault analysis based on DFRs are:

- Saves data processing time. Different situations and events in power system can result in lots of DFR recordings. Automated analysis allows users to focus on more important tasks by saving time on routine data processing tasks.
- Improves analysis performance. Automated processing and user notification that points to the problems in rather specific terms makes the analysis consistent and helps quick system restoration and reduces down time.

3. USE OF INTEGRATED SUBSTATION DATA

3.1 Data

A substation automation system has been implemented as shown in Figure 3. IEDs are installed at a substation with 345KV transmission lines connected to the buses in a breaker and a half scheme.

More detailed wiring of the IED configuration is depicted in Figure 4. The figure represents one end of a transmission line coming from a substation. Power system components involved are a bus, a transmission line, CTs and CCVTs to obtain analog measurements on the line, and a circuit breaker (CB). Following IEDs are used in this scenario:

- DFR, which monitors line voltages and currents as well as contact status signals such as relay trip, breaker auxiliary, and carrier send/receive;
- DPR, which monitors line voltages and currents, contact status signals related to protective relaying function (trip, carrier send/receive), as well as the external/internal status signals of the protective relay (starting elements, targets,).
- CBM, which monitors line currents going through the circuit breaker, 52a & b contacts, X & Y coils, DC power supply at the breaker, trip command, trip coil current, etc. [Kezunovic et al, 2005]

Generally, a DFR monitors most of these signals for all the lines (or at least the most important ones) and gives a comprehensive overview of the signal changes for the whole substation. Each protective relay monitors only signals related to the transmission line where they are installed. A relay does not "see" the signals related to other system components, but the relay recording provides much more details about its own operation (time-stamped log of all the status changes of internal/external elements, and oscillography as seen by the internal logic of the relay).

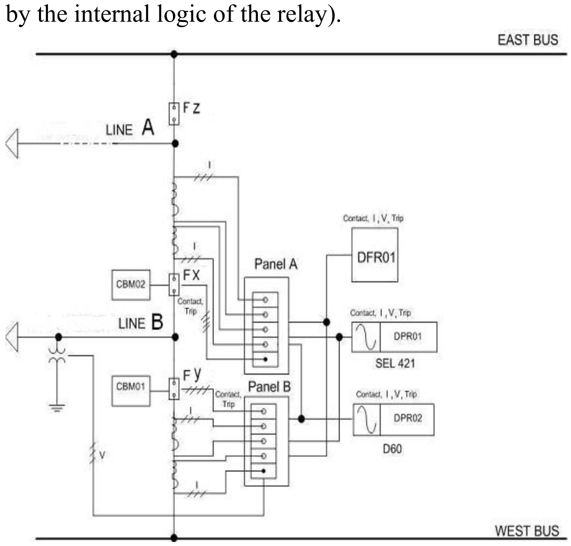

Fig. 3 Breaker and a half substation scheme

A CBM in this configuration monitors control status signals related to a selected circuit breaker. Similarly to the DPR which provides additional details about relay operation, CBM provides further details about each operation of monitored circuit breaker. Each of the devices might operate (and typically would) on different sampling rate and have different recoding length. That is why it is critical to have all the IEDs synchronized to an external time reference (through a GPS for example) to enable waveform alignment and comparison.

In this particular example, it is assumed that the IEDs are connected to a substation PC as shown in Figure 5. This allows for the synchronization and time stamping of all the files automatically transferred from the IEDs connected to the PC. In addition, all substation PCs can be connected to a main server located in central offices.

The data from all IEDs is transferred automatically to the Substation PC via serial RS233 and Ethernet connections and protocols supported by client part of substation automation software – AEAClient and IED vendor applications. AEAClient software is constantly running on the Substation PC and provides for automated retrieval of IED data, as soon as the fault/substation event triggers the recording. Additionally, AEAClient software performs local processing of the data and enables their transfer to remote centralized location. The local processing consists of the conversion of the recorded files into the IEEE COMTRADE file format [IEEE, 1999] and their renaming according to the IEEE recommended convention for time sequence data [IEEE, 2006]. In addition, automated classification of the data is performed based on the IED type, recording file type (waveforms, event report, fault report) and completeness of recording (complete, incomplete). The incomplete data is usually discarded. The transfer of the data to the remote centralized location (Control Center, Protection Engineer Office) is performed using a secure, flexible methods based on available utility communication infrastructure and adopted IT and network security policies.

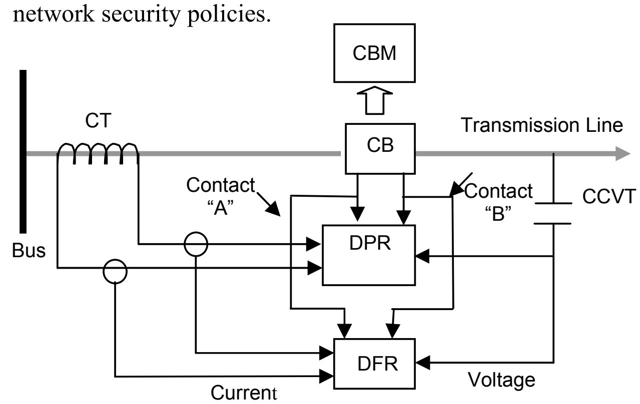

Fig. 4 Example IED configuration on a single line

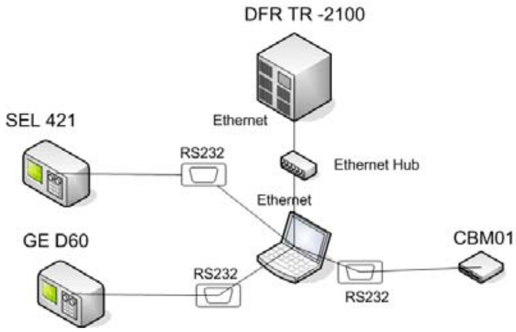

Fig. 5 IED data synchronization

3.2 Functions

The fault analysis function is performed at the remote location by AEAServer application and is based on IED data acquired from multiple substations to extract type, location and other relevant fault information. In current implementation, to perform the fault analysis function, the AEAServer application uses third party software – DFR Assistant [TLI, 2003]. Table 1 bellow shows different types of faults in cases of equipment failures, analyzed using DFR Assistant software integrated with AEAServer application.

Fault Type	Fault Location	Protection Zone	IED/Equipment Failure
AB	50	Z1	Main Relay Failed to Trip
ABG	70	Z1	Backup Relay Slow
AG	80	Z1/Z2	Middle Breaker Stuck
BC	60	Z1	Middle Breaker Stuck
ABC	60	Z1	Middle Breaker Stuck
AG	40	Z1	Middle Breaker Slow

Table 1 Types of simulated and analyzed faults

3.3 Displays

The AEAClient display showing list of IED data acquired in the substation is given in Figure 6.

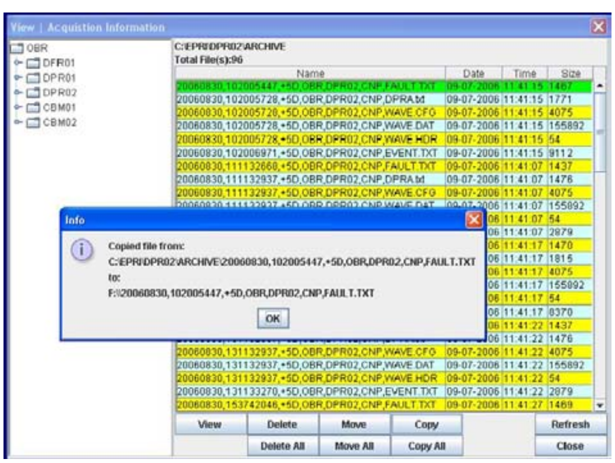

Fig. 6 AEAClient list of acquired IED data

3.4 Benefits

The implemented system allows for automated acquisition, integration, analysis and archival of all IED data available in the substation. This IED data can be used to improve the accuracy of existing fault detection algorithms and verify correctness of fault clearance operation by:

- Comparing same data (fault currents and voltages, breaker statuses, relay trip signals) obtained from different sources/IEDs in one or more substations
- Verifying the sequences of signals and equipment operation at substation level as seen by different IEDs

The system architecture allows for integration of other types of devices available at substation/system level, as well as different third party analysis applications.

3. USE OF ENTERPRISE-WIDE DATA

4.1 Data

Typical power system contains at least several hundreds of transmission lines. Installing recording devices at each transmission line is very expensive and it can not be found in practice. It is common that DFRs, placed in critical substations, record voltages and currents on several transmission lines. Protective relays are spread all over the system, but still most of them are electromechanical and do not have capability to record measurements. So in some cases it can happen that there are no recordings available close to a fault, while for the other cases measurements from both sides of faulted line are available. For a case shown on Figure 7, different DFRs are triggered but they are all away from fault location.

Depending on data availability, different fault location (FL) algorithms are applicable but their accuracy is dictated by availability and accuracy of input data. New approach for fault location using sparse measurements is proposed [Kezunovic et al, 2001]. According to available input data, different algorithms are evaluated and an optimal one is selected. The proposed solution requires external tools to meet an optimal performance of each algorithm. Architecture of the solution is shown on Figure 8.

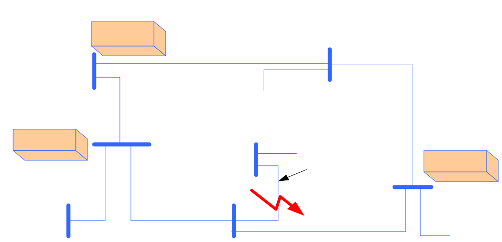

Fig. 7 Layout of DFRs closest to a fault on Line 1

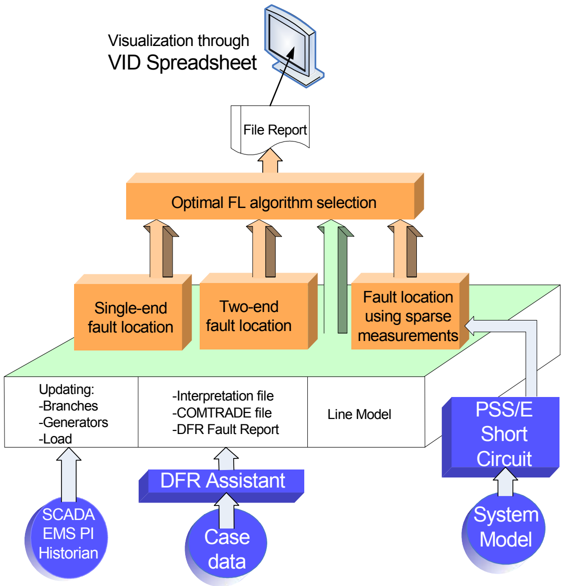

Fig. 8 Architecture of proposed solution

External tools module consists of:

- SCADA EMS PI Historian used for obtaining the pre-fault load, branch and gen. data in order to update system model before FL calculation starts.
- DFR Assistant [TLI, 2007] provides new event recordings from central repository in COMTRADE format [IEEE, 1999] and preliminary fault report. Report describes behavior of protection equipment, recognizes fault type and it is used FL algorithms as input file.
- PSS/E Short Circuit program [PTI, 2001] is accessed by some FL algorithms in order to run power flow and short circuit analysis automatically.
- System model in PSS/E format is updated before any calculation starts in order to reflect system state prior to a fault. This is important especially if topological changes took place in the mean time.

It can be noticed from Figure 8 that proposed solution has modular architecture, which enables expanding this solution with additional segments. As shown in the integration of substation IEDs section, recordings from different IEDs (DFR, DPR, and CBM) are available in a central repository. Processing additional data collected from these devices would provide more information about protection equipment that has operated. This information could be very useful for reducing size of possible fault location area; understanding nature of fault and it could be applied as input parameter for FL algorithms.

4.2. Functions

Beside external tool module proposed approach has one more segment, fault location module, as Figure 8 shows. Once new data is obtained from DFRs, fault location module is triggered automatically. It updates status of power system topology according to the retrieved data from SCADA and runs the most suitable fault location algorithm. Some of the used FL algorithms are immune to fault resistance, some have accuracy that varies with line length, and some depend on the use of short circuit programs. To calculate the FL most accurately, an automated procedure for selecting the best FL algorithm for a given circumstance is developed. FL algorithms that are used as a possible selection include:

- Synchronized sampling two-ended algorithm [Kezunovic et al,1994] belongs to time based methods and it uses both lumped and distributed model depending on transmission line length. This algorithm is based on fact that the voltages and currents from one end of the faulted line can be expressed in term of the voltages and currents of the opposite end. This algorithm does not depend on any setting, which makes it very robust, and results are very accurate (obtained error is 0.5% in most cases [Kezunovic et al, 1994]).
- Unsynchronized sampling two-end algorithm [Novosel et al, 1996] uses un-synchronized post-fault phasors for FL estimation. It can be applied on both short and long transmission lines. Its accuracy will be affected the most by accuracy of transmission line model. It gives good results in presence of fault resistance and fault type doesn't need to be known.
- System-wide sparse measurement algorithm [Kezunovic et al, 2001] is applicable on sparse measurements. This algorithm is based on waveform matching method. In order to utilize this method, genetic algorithm optimization approach is used. This algorithm is affected by fault type; it gives better results if possible faulted area is known. By analyzing CB behavior or using roughly calculated fault location, it is possible to narrow down possible faulted area and apply this algorithm. If input is correct it can give very accurate results although only sparse measurements are available.
- Phasor-based single ended algorithm is applicable in the most common situations when recorded data are available only from one end of a line. One of the well-known algorithms of this type is presented in [Takagi et al, 1982]. Since this algorithm had several constraints like necessity of having prefault current recordings or assumption of constant fault impedance, which is not always true, it was necessary to develop better one-end FL algorithm using symmetrical components. These algorithms require relatively simple calculation and their implementation is not tedious. Their accuracy depends on the simplified assumptions, but in many cases they yield good accuracy.

In order to reduce outage time the proposed approach provides additional capability: Visual Interactive

Distributed (VID) Spreadsheet. This module translates results from fault location file report into view of corresponding faulted area. Through this tool it is possible to see physical environment of faulted area and behavior and status of equipment involved in the fault event. Fault location is shown through 2D and 3D view. It is possible to interact though these views by rotating them and zooming in and out. Examples of developed display are shown on Figures 9 and 10.

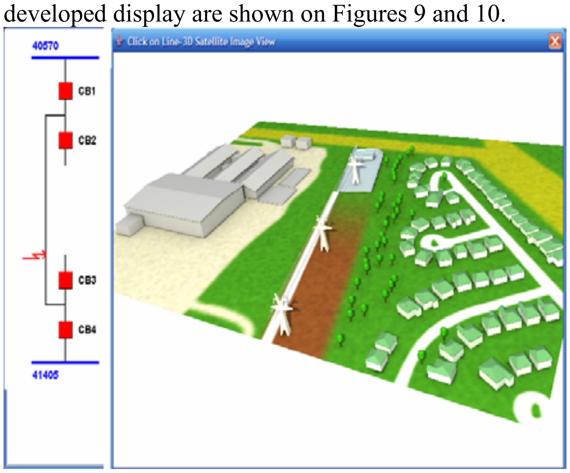

Fig.9 3D view of fault location area

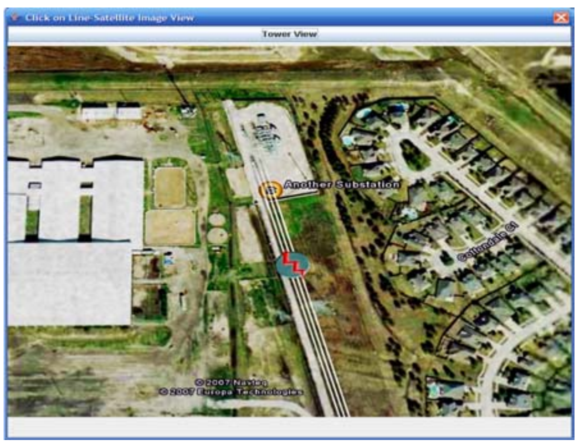

Fig.10 2D view of fault location area

Benefits

The following is a summary of the benefits achieved with this new solution:

- *System operators:* Their main tool today is the SCADA system. Additional information from the VID spread sheet is obtained using additional data from substation Intelligent Electronic Devices (IEDs). This will speed up decision made by operator in restoring the system.
- *Protection engineers*: Instead of spending a lot of time on processing IED data manually, this group will be unburdened from the routine analysis tasks that will be performed automatically and will able to concentrate on complicated cases that require their involvement.
- *Maintenance staff*: Through equipment view they would be able to understand behavior of equipment and its status and will be able to immediately take some actions, instead of waiting for instructions from other groups. This will significantly reduce the time spent on fault repair and system restoration

CONCLUSION

The paper introduces three different approaches to automated fault analysis. It has been demonstrated that each approach yields different benefits. The paper points out that careful consideration is needed before deploying the solutions since the outcome heavily depends on the type of data used.

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References

IEEE, 1999 "IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems", IEEE Std. C37.111-1999

IEEE, 2006 "Draft Recommended Practice for Naming Time Sequence Data Files," IEEE PC37.232/D8, 2006

Kezunovic, M., Perunicic, B., Mrkic, J., 1994 "An Accurate Fault Location Algorithm Using Synchronized Sampling," *Elec Pow. Sys. Research Journal,* Vol. 29, No. 3, pp 161-169, May 1994.

Kezunovic, M., Liu, C.C., McDonald, J., Smith, L.E., 2000, "Automated Fault Analysis," IEEE Tutorial, IEEE PES, 2000.

Kezunovic, M., Liao Y., 2001 "Fault Location Estimation Based on Matching the Simulated and Recorded Waveforms Using Genetic Algorithms," Dev. in Pow. Sys. Prot., Netherlands, April 2001.

Kezunovic, M., Ren, Z., Latisko, G., Sevcik, D.R., Lucey, J., Cook, W., Koch E., 2005 "Automated Monitoring and Analysis of Circuit Breaker Operation," *IEEE Trans. on Power Delivery,* Vol. 20, No. 3, July 2005, pp 1910-1918.

Novosel D., Hart D.G., Udren E., Garitty J., 1996," Unsynchronized two-terminal fault location estimation ", Power Delivery, IEEE Tran. on Volume 11, Issue 1, Jan. 1996, Page(s): 130 - 138

PTI, 2001 "PSS™E Load Flow" Siemens Power Transmission & Distribution, Inc., Schenectady, NY, USA

Takagi T., Yamakoshi Y., Yamaura M., Kondow R., Matsushima T., 1982" Development of a New Type Fault Locator Using the One-Terminal Voltage and Current Data", IEEE Trans. on Pow. App. and Sys., Vol. PAS- 101, No. 8, Aug. 1982 pp 2892-2898.

TLI, 2003: "DFR Assistant - Software for Automated Analysis and Archival of DFR records with Integrated Fault Location Calculation", [Online]. Available: *http://www.tliinc.com*