Automated Fault and Disturbance Analysis: Understanding the Configuration Challenge

M. Kezunovic, *Fellow*, *IEEE*, S. Sternfeld, M. Datta-Barua, *Member*, *IEEE*,
D. Maragal, *Member*, *IEEE,* and T. Popovic, *Senior Member*, *IEEE*

***Abstract* - Whenever a fault or disturbance in a power system occurs several IEDs are triggered and several data recordings are generated. Automated processing and analysis of substation disturbance data is an effective way to filter important information from the collected data and convert the extracted information into knowledge. Configuring automated analysis systems to allow for efficient data integration and analysis of substation data in timely fashion has been recognized as a challenge.**

Implementing automated fault and disturbance analysis requires continuous and proper handling of the configuration settings. To process substation IED data we need to know relevant IED settings, channel assignments, and parameters of the power system components being monitored. The paper discusses configuration challenges pertinent to automated fault analysis solutions as they were implemented in three utilities over the years.

***Index Terms* — smart grid, substation automation, power system faults, power system monitoring, substation data mart, automated fault analysis, fault location, circuit breaker**

I. INTRODUCTION

Automated fault and disturbance analysis is an effective way of going through digitally recorded field data related to a fault and identifying the circuit with the highest disturbance, then performing the cause-effect analysis between fault waveforms and relay operation, and eventually locating the fault with high precision. In many utility companies today the process of the analysis is done manually requiring extensive investment of time of human resources, a scarce commodity in today's business environment in the power system industry. Automating the analysis process leads to tangible benefits in saving the time of personnel, improving consistency of the analysis process, and shortening the time needed to locate the faults, repair the damage and restore the service. This opportunity is particularly attractive as an increasing number of intelligent electronic devices (IEDs) capable of recording the field data are becoming widely available across the utility systems making a thorough manual analysis with the existing personnel resources virtually impossible. This creates a business case for streamlining the analysis process and automating the various stages from collecting and integrating data to performing analysis and archiving the results. As much as the automation opens new possibilities about how to handle the data to produce the results effectively, there are implementation challenges: how to communicate with diverse devices and retrieve data in timely fashion, how to convert data into information while following all the requirements and standards, and finally how to use this information in the best possible way.

In order to provide both substation data integration and automated analysis, the solution requires proper handling of the configuration data. Several aspects of configuration data need to be addressed: configuration of the power system components such as transmission lines, buses, transformers, and the configuration details on how particular devices are connected. The components of the automated analysis solution and their parameters are constantly going through small or big changes, upgrades, firmware updates, etc. These changes need to be properly reflected in the configuration of the solution for data integration and automated analysis. The same changes are typically affecting other analysis applications as well (short circuit study programs, simulation tools, PI historian, etc.) Yet another aspect are the changes of the standards and recommendations (IEEE, NERC, FERC) that are constantly evolving and taking into account different aspects and possible uses of the substation data.

This paper addresses the challenges of handling the configuration data and illustrates the issues with examples from field experiences. In addition to the existing solutions the paper discusses possibilities and

Mladen Kezunovic is with Texas A&M, College Station, TX, USA (e-mail: kezunov@ece.tamu.edu)

Scott Sternfeld was with FirstEnergy Corporation, Akron, OH, USA (email: scott.sternfeld@gmail.com)

Manjula Datta-Barua is with CenterPint Energy, Houston, TX, USA (email: manjula.datta-barua@centerpointenergy.com)

Deepak Maragal is with New York Power Authority, White Plains, NY, USA (email: deepak.maragal@nypa.gov)

Tomo Popovic is with Test Laboratories International, Inc., College Station, TX ,USA (email: tomo@tli-inc.com)

directions on how the system configuration data can be handled by other system wide solutions such as PI historian data base, or short circuit study programs. The discussion in the paper will help the users understand the value of configuration data and how to make it readily available for use by the automated analysis solutions.

II. Background

An example of a solution for automated fault and disturbance analysis implemented at substation data level is depicted in Fig. 1. Fault data can be obtained from DFRs and/or DPRs, as well as other event recording IEDs [1,2]. The main functions of the solution can be divided in following groups:

- Processing and Analysis Logic (IED specific),
- Data Manager,
- Data Warehouse,
- User Interface, and
- Two-end Fault Locator.

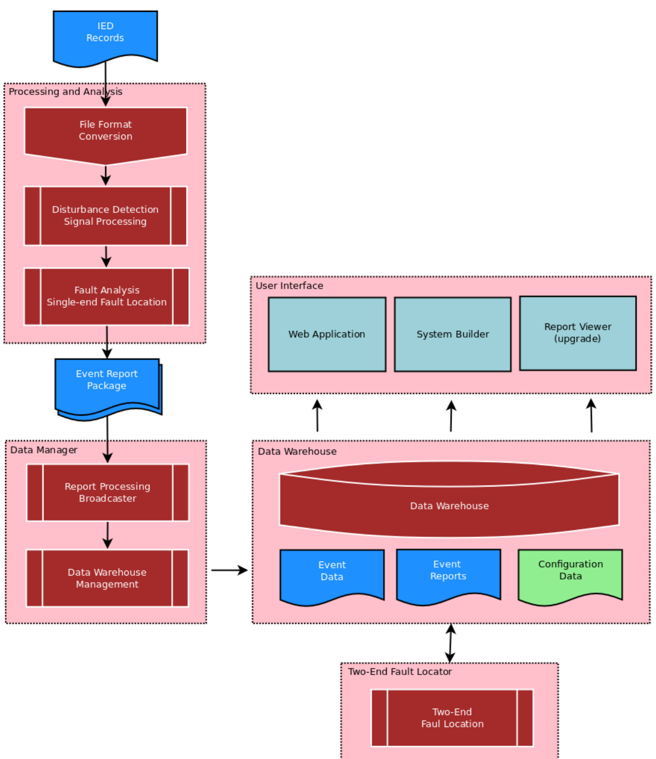

Fig. 1. Automated fault and disturbance analysis solution

Processing and Analysis Logic. All the IED records are being automatically converted into a unified non-proprietary file format [3,4]. Signal waveforms, namely voltages and currents, are being mapped to monitored power system components (transmission lines, transformers) and the processing includes fault type detection, disturbance classification, and single-end fault location calculation [5]. There could also be a processing and analysis software module for each IED type group (DFR, DPR, CBR, etc.) and these modules typically correspond to IED level functionality.

Data Manager. The Data Manager is responsible for broadcasting reports and proper maintenance of the data warehouse and centralized repository. In addition, it provides functions for broadcasting notifications to selected users via email and/or pager service.

Data Warehouse. All the converted event data, analysis reports, and system configuration are kept in the data warehouse. The data warehouse implementation utilizes a standard database engine and a centralized file repository. Keeping the event data in non-proprietary standard file format [3,4] enables direct access and use of fault data even with standard file managers such as Windows Explorer.

User Interface. The main user interface can be web-based and enables users to access data warehouse utilizing just a standard web browser (for example, Internet Explorer or Firefox). Optionally, user interface can combine web-based and desktop-based technologies (thin and rich clients) depending on specific user needs and preference.

Two-End Fault Location (Optional). The two-end fault location function is attached to data manager and implements phasor-based two-end fault location calculation [5,6]. The actual function is triggered by an occurrence of fault data being available from both ends of the transmission line within a pre-defined time window. It is crucial that the fault data is correctly time stamped before being processed. Time stamps are used while the data warehouse is searched for pairs of DFR records that come from two ends of the same transmission line and correspond to the same fault event. The actual operation of the function is triggered by occurrence of a DFR data record and report created by the analysis software module from one end. The two-end module is reaching beyond a single substation level because it is combining data from two substations corresponding to two ends of the faulted line. Thus it could be considered as an automated function at the system level.

To put a system like this together and enable automated processing and analysis of fault and disturbance data it is necessary to correctly specify, configure and maintain all the configuration settings. Not only is it important to have a configuration in place at the time of deployment but it is also important to make sure that a solution can be expanded and survive continuous changes and upgrades.

Following sections discuss implementation of solutions for automated fault and disturbance solutions from the configuration perspective.

III. Communication Configuration

Communication to substation IEDs and automating collection of fault and disturbance records is probably one of the biggest challenges. Introducing networks into substations may violate network security principles for an automation system environment in the substation. User IDs, password management, and access management can become significant obstacles. Passwords that must change periodically, lock out access after login failures, or other cyber security requirements may impact the operational effectiveness of a substation network. Typically, power utilities have a full set of their internal security polices. When implementing automated data integration and analysis solution these internal security polices need to be taken into consideration. Another challenge is that some of the IEDs such as digital fault recorders were installed a long time ago and there is no proper communication infrastructure in place.

Network cyber security is a significant issue that may pose an unacceptable risk to those who believe it is impossible to adequately secure the substation network. While cyber security is a major concern, the risks should be completely identified and mitigated in order to adequately protect the substation network from cyber-attacks. This is becoming one of the major issues and concerns since all of the companies are now making changes to conform to various cyber security requirements. Some companies prefer to resolve the cyber security issues and achieve full compliance with NERC and other external regulations prior to implementation of automated data integration and analysis [7,8].

Some IEDs such as DFRs could be considered as non-critical assets and possibly have relaxed cyber security requirements. Others such as protective relays fall into critical assets and are treated with tight cyber security requirements. Proper understanding of both internal and external cyber security requirements is critical both when planning monitoring in new substations, as well as when trying to automate data collection from previously installed IEDs. The communication configuration to accommodate cyber security requirements needs to be well defined and understood in order to have comprehensive implementation of the automated data analysis systems.

IV. Fault and Disturbance Analysis Settings

In order to make it possible to implement fault and disturbance analysis starting from substation level and up, we need to have correct monitoring and disturbance recording in place. In order to automate the analysis in addition to disturbance recordings we need to know or have an access to current and correct configuration information. For example, if we consider a transmission line, a possible set of input signals needed for automated analysis is illustrated in Table 1. Disturbance records should include analog measurements such as line currents and voltages. To be able to properly detect fault type on a transmission line we need to have three-phase measurements (i.e. for line current monitoring: three phases or two phases and zero sequence current). To employ a more sophisticated disturbance analysis it is recommended to monitor additional signals such as breaker statuses, relay trips, and protection scheme related statuses.

TABLE I

Input Signals to Disturbance Analysis

Signal	Description	Type
Ia, Ib, Ic, I0	Three phases or two phases and zero sequence	analog
Va, Vb, Vc, Vn	Three phases or two phases and neutral	analog
CBP	Bus (primary) or main breaker	status
CBS	Middle (secondary) breaker	status
PRT	Primary relay trip	status
BRT	Backup relay trip	status
TCR	Blocking signal received	status
TCT	Blocking signal transmitted	status
TCFR	Breaker failure signal received	status
TCFT	Breaker failure signal transmitted	status

If we extrapolate the transmission line example to implementation of automated analysis of disturbance monitoring in whole substation it is easy to conclude that our automated fault and disturbance analysis solution needs to have an access to the following:

- Substation fault and disturbance records as they are generated (data files).
- IED specific settings at the time of the disturbance recording (channel assignments, scaling).
- Power system component parameters (i.e. line impedance, line length, mutual coupling).

- Context in which the recorded disturbance and configuration can be analyzed (i.e. circuit, type, protection scheme).

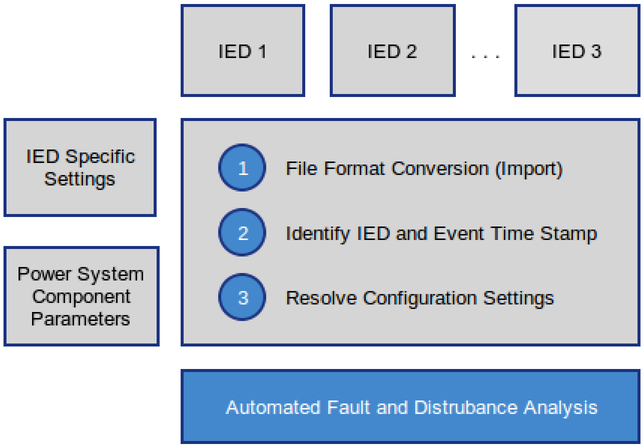

Fig. 2. Matching disturbance recordings with configuration

Assuming that the communication to substation IED and automated data collection is in place the disturbance data collected in substations needs to be matched with corresponding IED specific settings as well as correct and current power system component parameters (Fig. 2).

IED specific settings sometimes do come within disturbance recordings, but it is not unusual to have those in separate file, sometimes even kept on a separate computer. One of the important points here is to raise user awareness of the importance to have easy access to IED settings in order to enable manual or automated disturbance analysis. Current work on a new COMTRADE standard addresses this issue. Special attention is needed when dealing with multiple IED units within a substation. Field experiences revealed situations when some circuits (i.e. transmission line) are not fully monitored by a single unit, but multiple units. For example, we encountered cases when current was monitored by one DFR unit and voltage by another. This may look like a non-consequential example, but might turn into a complicated problem when configuring automated analysis. First, if this is the situation we have to make sure that multiple units are correctly configured for cross-triggering (all units produce a record if one triggers). Second, the data collection software has to be configured to download all of the records together and even provide merging of the records into a single file. If merging option is not available, it is still possible to artificially analyze and merge separate records from multiple units, but this can be very challenging with respect to time synchronization, sampling rates, number of samples in each file, etc. A "rule of thumb" when installing new IEDs is to make sure that each logical power system component is fully monitored by channels on single IED or to enable cross-triggering and correct data merging within the data collection software.

Interesting field experiences emerged when the solution was installed at the top of the existing IED setup. Installed IEDs, although similar models and vintage, had different firmware versions and raw data had some discrepancies in the file format. Problems like this are more visible when dealing with a mixture of legacy and modern IEDs, as well as when new IEDs are being added to the system.

Another important set of parameters is description of power system components. In our example of analyzing disturbance on a transmission line, we need to know the line impedance and line length in order to be able to automatically run fault location calculation. Both types of the configuration settings can be part of the solution's settings, or can be implemented by interfacing to other systems such as short-circuit study programs, PI historian, 61850 SCL, etc [9,10].

It is important to understand that automated analysis solutions have configuration changes over time. The monitoring system containing substation IEDs is constantly expanding and being maintained. Also, the power system equipment is continuously changing as well. Not always at the same pace, but change is inevitable.

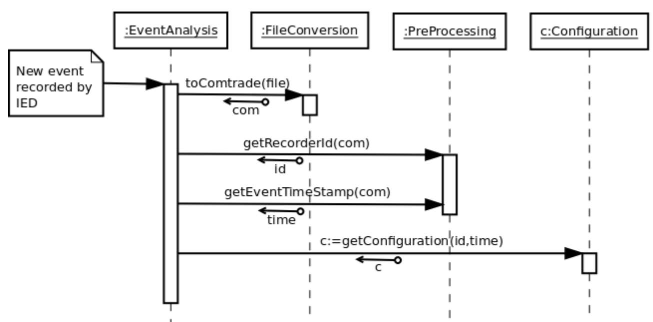

Fig. 3. Sequence diagram: obtaining IED configuration

From the prism of a solution for automated fault and disturbance analysis, our solution configuration repository needs to accommodate configuration change management and maintain history of solution's configuration over time. For each disturbance record we need to be able to locate a corresponding set of configuration parameters that can be used for automated analysis. Fig. 3. depicts simplified UML sequence diagram for obtaining IED configuration settings. Each IED record is first converted into non-proprietary COMTRADE file format. Then the preprocessing provides unique IED identification (id) and event time stamp (time). Those two parameters (id and time) are then used to retrieve corresponding configuration settings used for automated analysis.

V. User Interface options and Settings

The proposed concept enables different types of users to access the fault and disturbance data utilizing customized user interfaces. Different users, belonging to various utility groups may have a need to access different disturbance data and analysis functions. The level of details about the event is where they all may differ to a great extent even though the initial event data is the same. Customized electronic and paper reports can be generated depending on the user needs. Figure 4 illustrates how utilizing new web technologies the user access to the database may be implemented as web-based application meeting particular needs as well as access privileges [11]. In some instances it is even possible that the users can belong to the same user group but may have different information needs and/or access privileges. The key for proper visualization is in the design and contents of the integrated substation data warehouse. The integrated disturbance data and analysis reports should be stored in such a way that it is easily accessible and can be queried and retrieved by various existing and even future visualization tools. The analysis reports should be in readable and non-proprietary format (ASCII, DOC, PDF) and stored back into the data warehouse. It is highly recommended to utilize proper file naming and database referencing for possible future use and reuse of the output reports.

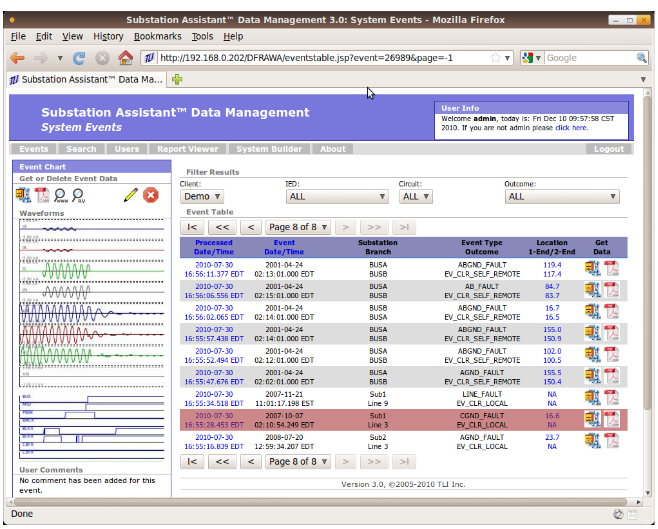

Fig. 4. Customized web-based user interface

Visualization and user interface can be implemented as client-side application executing visualization application or user interface on client computers (Fig. 5). Typically, visualization application is installed on the client computer also known as “rich” client. Benefits are that such applications may provide better control and handling of data, but a disadvantage is that all of the client computers may have to conform to certain requirements and even go through client software installations and software updates. There are also technologies such as Flash or Java that allow for running rich client applications loaded from a server (no need for local installation or updates).

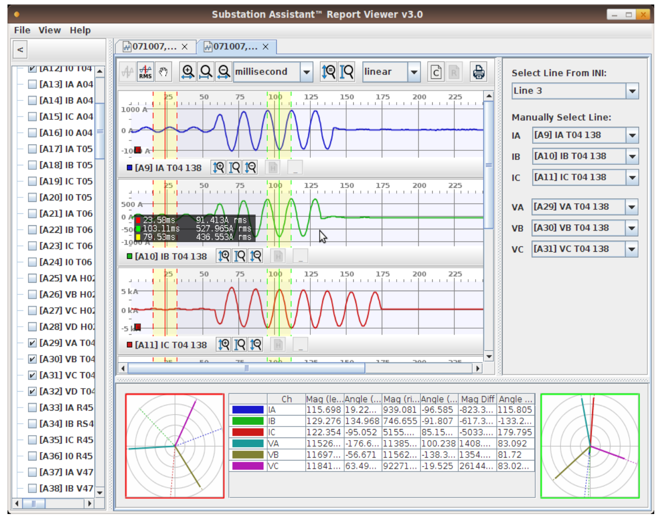

Fig. 5. Desktop-based (from local Intranet) user interface

Fig. 6. Disturbance analysis “on the go” via email or text

Direct notifications to users and reports customized and formatted for particular user groups should be done using all the available technology means. Additional “intelligence” may be incorporated into reports disseminated based on event priorities and user category. It is expected that the solution provides for web reporting via corporate network using web-based user interface (Fig. 4). Notifications are expected to be sent via fax, email, mobile pagers and printers. Email and web reporting can be very powerful tool for analysis “on the go” when combined with smart phone technologies (Fig. 6).

Different internal (company polices) and external (NERC, FERC, etc.) standards and recommendations may be applicable on how reporting needs to be done and what templates and formats the reports need to follow [12]. Those requirements should be taken into the account and where feasible be implemented as part of automated processing and user interface settings.

VI. Lessons Learned

The paper emphasizes the important issue of configuring solutions for automated fault and disturbance analysis. An example implementation of a solution for automated fault and disturbance analysis is described and used to illustrate configuration challenges. This solution has been installed and used in the field, so the comments and notes in this paper come from the field experience:

- ***Early deployment*** in a system with around 20 DFRs. DFRs included three vendors with different models and vintages. Several issues were encountered with data communication; file format conversion, unique identification of DFRs, and addressing the cyber security.
- ***Going from a pilot to system-wide solution*** in a system where implementation went from two substations (pilot setup) to around 50 substations. The pilot included both DFRs and digital relays, while the expansion includes mainly DFRs. Gradual incremental approach to the implementation displayed several benefits when dealing with both internal and external requirements.
- ***Maintaining existing system-wide solution*** where the solution has been deployed for more than 10 years. Main lessons regarding dynamic changes of the configuration were learned here. Both the power system and monitoring solutions (various models and vintages of IEDs) change over the time and the configuration changes have to be addressed accordingly.

VII. Conclusions

The paper discusses configuration issues for the fault and disturbance analysis solutions. The main aspects of the configuration challenge are illustrated through a system for analysis of substation IED event records and transmission line faults. The following are key observations:

- Each IED record has to be uniquely matched with the corresponding IED and time stamp, which is needed for retrieval of the configuration settings.
- The configuration settings typically require: a) IED specific descriptions, and b) power system component parameters. Both types of configuration settings data are critical for automated analysis.
- IEDs, as well as their configuration (wiring, channel assignment, triggering, etc.) are continuously added, upgraded, and changed. Hence, IED configuration needs to be maintained continuously.
- The power system components are being added and changed over time. Therefore, proper version control of the configuration settings data has to be in place.

VIII. Acknowledgements

The authors would like to thank Mr. Brian Clowe from CNP, Dave McCartney from FE, and Mr. Matt Kuhn from TLI, Inc. for their contribution to the system implementations described in this paper.

IX. References

[1] M. Kezunovic, T. Popovic, *"Substation Data Integration for Automated Data Analysis Systems",* IEEE PES 2007 General Meeting, Tampa, Florida, June 2007.

[2] D. Maragal, B. Fardanesh, *"Automated fault data collection, analysis, and reporting"*, IEEE Power & Energy Society 2009 General Meeting, Calgary, Canada, July 2009.

[3] *IEEE Standard Common Format for Transient Data Exchange*, IEEE Standard C37.111-1999, 1999.

[4] *IEEE Recommended Practice for Naming Time Sequence Data Files,* IEEE PC37.232-2007, 2007.

[5] *IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines*, IEEE Standard C37.114-2004, 2004.

[6] J. G. Webster, et al., *Wiley Encyclopedia of Electrical and Electronics Engineering*, A Wiley-Interscience Publications, John Wiley and Sons, Inc., 1999.

[7] *NERC Standard, Cyber Security,* North American Electric Reliability Corp.

[8] *NIST IR 7628*, "Guidelines for Smart Grid Cyber Security", NIST Computer Security Division – Computer Security Resource Center, [Online]. Available: http://csrc.nist.gov

[9] PI System™ Software, [onine]: http://www.osisoft.com

[10] *IEC Std. 61850*, "Communication Networks and Systems in Substations", work in progress, International Electrotechnical Commission, [Online]. Available: http://www.iec.ch

[11] Substation Assistant™ Software, [online]: http://www.tli-inc.com

[12] *NERC Standard, Protection and Control,* North American Electric Reliability Corp.