

Substation Automated Data Analysis: Deployment Challenges

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Abstract - The paper focuses on deployment challenges for automated substation data analysis solutions. Through examples from recent deployment projects, the paper discusses the fact that both the utilities and suppliers are dealing with a set of requirements defined as a compromise between the needs of variety of in-house stakeholders. These requirements are prone to changes and that itself is one of the biggest challenges. In addition, the deployment is almost always faced with unexpected challenges from the production environment itself.

The paper illustrates a gradual step-by-step approach from a solution demonstration to the production deployment. The first part focuses on the solution that analyzes digital fault recorder and digital protective relay data. In-house testing with both simulated data and with the data obtained from the field is discussed. The second part of the paper discusses implementation and deployment of a new circuit breaker recorder aimed at on-line monitoring circuit breaker operations.

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

I. INTRODUCTION

There are several steps involved in solving the challenge of substation data integration and automated processing and analysis [1], from identifying and specifying all the system requirements to the solution demonstration, and finally, full deployment. This paper focuses on the deployment phase and covers the practical issues and real experiences from bringing an actual solution for automated substation data integration and analysis to every day use.

The latest updates from NERC, along with other external or internal requirements helped narrow down the options for deployment. When handling event data from intelligent electronic devices (IEDs), special attention should be paid to NERC PRC-002 and PRC-

018 requirements [2] (now combined under new version of PRC-002), as well as CIP-002 though CIP-009 standards related to cyber security [3]. In addition, IEEE file format standards IEEE C37.111-1999 (COMTRADE) and IEEE PC37.232-2007 (file naming convention) is of essence when deploying a solution that includes warehousing of substation IED event data [4,5]. These topics are addressed in the paper and illustrated with experiences from the field deployments.

The paper identifies the main steps for the deployment as well as the use: a) feeding the substation IED data into the automated substation data integration and analysis software; and b) making the results available to variety of users or user groups. Utilizing non-proprietary data formats and keeping the system interfacing open allows for further improvements after the deployment. The paper addresses a need for and benefits of a universal user interface for viewing both the data and analysis results.

Various aspects of timing issues are also addressed: time stamping of IED data, and times needed to automatically collect and process IED data. The importance of having all the IED data time-stamped with correct time information is illustrated with field examples. Some of the deployed functions may entirely depend on this, for example, two-end fault location calculation.

The collection and processing times are also very important and may be a key when considering the use of information from substation IED event data for operational purposes. Having IED data downloaded and processed within a few minutes or less could turn this typically non-operational data into operational information.

Finally, the paper summarizes experiences and findings from actual deployment. Several issues such as bad IED configurations, incorrect wiring, communication problems, cyber security and timing issues are and should be discovered throughout the deployment and commissioning process.

II. BACKGROUND

An example of a monitored transmission line is depicted in Fig. 1. The picture displays multiple IED types used in a substation. In this example: a digital fault

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recorder monitors all the transmission lines, transformers and buses, digital relays (primary and backup) at each end of the transmission line, and circuit breaker recorders monitor control circuits of main and middle breakers of each line configured in a breaker-and-half bus arrangement. Several IEDs may be triggered simultaneously to capture the same event. In the example in the figure it is assumed that the fault triggered recording at all IEDs connected to the monitored line. This in turn resulted in five records that correspond to the same fault, created in this substation. It is also possible that not all the IEDs would capture the event so four, three or less event files would be available in the case one of the relays or breakers did not operate. The figure is considering 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 least DFR 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 that all the IEDs can be coming from different vendors and vintages.

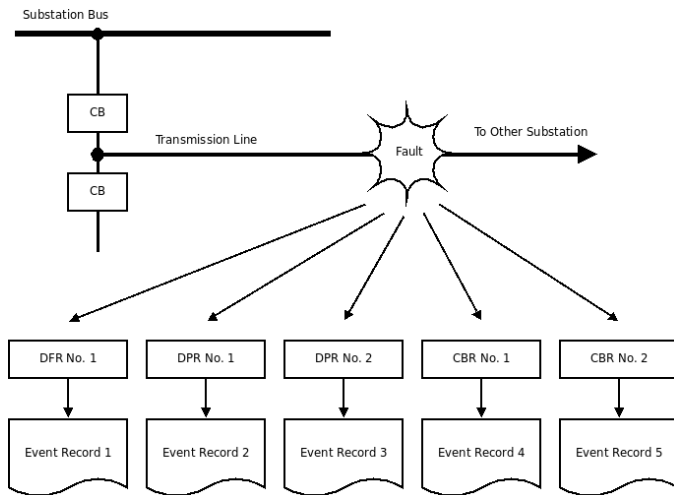


Fig. 1. Several event records captured for a single fault

III. DATA COLLECTION

Dealing with data coming from variety of IEDs manufactured by different vendors typically implies 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. NERC requirements for handling substation disturbance data as well as cyber security should be

consulted for proper implementation of communication and data collection. An important issue is that all substation event data should be properly time stamped using GPS clock information so that all of the event records can be sorted in historical orders as well as grouped into clusters of event files that correspond to single event [7].

Having the data collection process fully automated and making IED data available on the file server is only the first step for proper data integration. The second step is to bring all the data into the same format and make sure that a quick search and retrieval is possible. This process typically includes file conversion into a unified non-proprietary standardized file format and also requires knowledge of current system configuration [1,8]. The file conversion process for each type of IED can also be accompanied with device level analysis functions for more efficient implementation.

A very good choice is to make a “clean cut” between data collection, data conversion, and data processing to avoid interference among the different pieces of the solution “puzzle”. Automated data processing and analysis functions should be if possible decoupled from the data integration. The following sections discuss the importance of an in-house testing and verification prior to the deployment.

IV. IN-HOUSE TESTING PRIOR TO DEPLOYMENT OF AUTOMATED ANALYSIS FOR DFRs AND DPRs DATA

A. Using Simulated Test Data

It is not always an easy task to provide enough “good” test data obtained from field recordings, especially if testing requires recordings from both ends of transmission lines. The testing of the solutions for automated analysis of substation event data can be done using EMTP/ATP or MATLAB simulation tools [9,10]. Different fault types at different locations on a selected transmission line in the system model can be simulated. It is recommended to convert the simulated data into COMTRADE file format. Generated COMTRADE files are then presented to the solution, in this case, as recordings coming from two adjacent substations. These recordings created by simulation are processed by Digital fault Recorder/Digital Protective Relay (DFR/DPR) focused automated fault analysis and for each case single-end fault location was calculated. The two-end fault location algorithm calculation is initiated whenever the solution at the data manager level recognized availability of data from both ends. Tests with simulated data do provide functional testing of integrated solution, but do not provide full insight on how the system is going to behave with actual field data.

However, this approach builds a confidence needed to proceed with the deployment and eliminates quite a few issues ahead of the deployment phase.

B. Testing with Field Data

Once system functions are tested with simulated data it is recommended to verify both the system and configuration with the data obtained from an actual system by filed recording.

1) Use of DFR Data

In one of the cases the data is obtained from around 50 DFRs sparsely installed throughout the system, which means that it was not a common situation to get DFR data from two adjacent ends of the same transmission line.

TABLE I
EVENT LOCATION EXAMPLE: DFR DATA

Substation Assistant™ Analysis			
Event Time	Substation	One End Loc	Two End Loc
2007-03-14 18:34:39.169	Bus A	6.4 miles	6.7 miles
	Bus B	4.1 miles	4.6 miles

Around 33,000 DFR records were used for in-house evaluation. The files were copied in their native DFR file format, automatically converted to COMTRADE and processed and analyzed to identify disturbance type, fault type, evaluate system protection operation, and calculate distance to the fault [11].

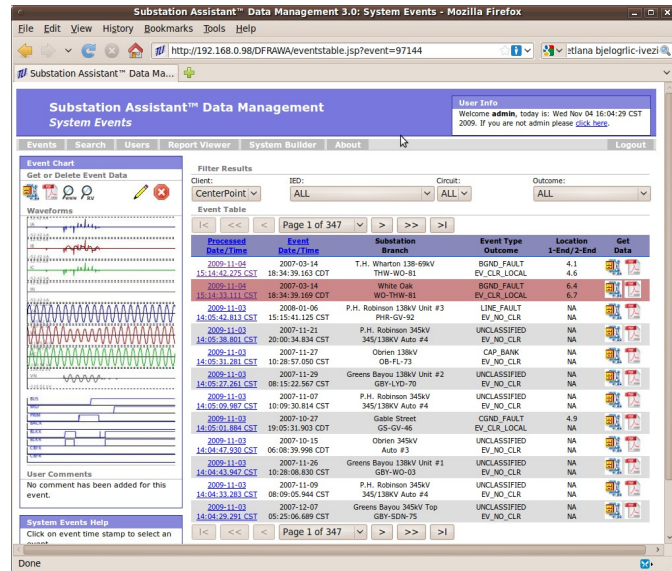


Fig. 2. Browsing IED (DFR/DPR) data via web interface

The calculated fault location was compared with the historical data, which was challenging since adequate field data were not available for most cases. In some instances, there was data from both ends of the line so a comparison between single- and two-end fault location

took place (an example given in Table I). The web interface for accessing integrated substation IED data is customized to allow easy access and overview of the results (Fig. 2).

2) Use of DPR Data

In addition to DFR data, manually collected files from 10 SEL and GE DPRs were used, too. Two-end data was 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 location calculation reports the fault data can be either extracted by parsing the reports, or actually calculated based on the oscillography data. For practical use it is important to know whether the oscillography recording has been filtered or unfiltered, and to try to obtain DPR data with the highest available sampling rate.

TABLE II
EVENT LOCATION EXAMPLES: PROTECTIVE RELAY DATA

Substation Assistant™ Analysis				
Event Time	Sub/Bus	One End Loc	Two End Loc	One End Loc
2008-05-14 04:40:38.48	Bus A	8.7 miles	8.2 miles	8.75 miles
	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

Examples of an actual processing and fault location calculation (single- and two-end) is given in Table II. The table shows comparison between single-, two-end calculation, and data parsed from digital relay reports. It is important to note that the two-end data obtained from SEL relays in this cases shows very good alignment with respect to the use of GPS synchronized clocks on both ends of the transmission line. The time difference for the event trigger was under 10ms. The highest available sampling rate was used and a very good match between calculated values and SEL reports is observed. An universal report and event viewer is utilized to enable easy inspection and manual analysis of IED records regardless of the IED type: DFR, DPR, CBR, etc. Special attention is needed when dealing with low sample rate data as it was the case with some relay data. This is illustrated in Fig. 3. The event viewer automatically applies linear or spline interpolation depending on the number of samples per cycle.

Typical processing time of an event file (DFR or

DPR) was less than a second. When looking from a deployment perspective the main challenge is to automate auto-poll (or auto-call) for obtaining IED event data automatically. Utilizing Ethernet and auto-call there is a possibility to dramatically reduce time from event occurrence to processed data and report showing up in the database. An obvious B-G fault was identified as C-G and all the calculated values were incorrect.

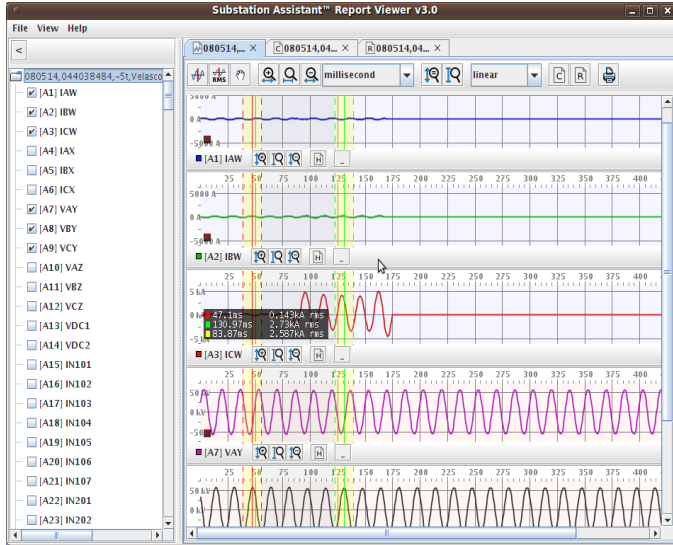


Fig. 3. Opening SEL files with universal event viewer

3) Use of DFR and DPR Data

An interesting benefit surfaced from another setup where both DFR and DPR data were available. An event captured by both relays and fault recorders resulted in “bad analysis” of the DFR data.

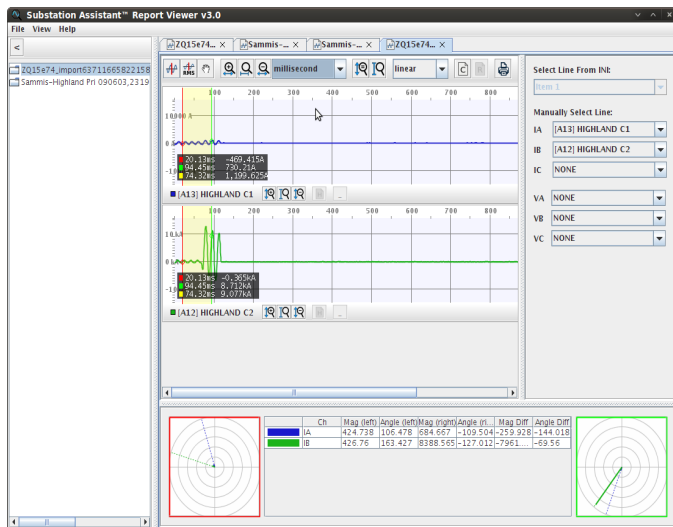


Fig. 4. Identifying incorrect wiring (B-phase)

Quick manual analysis of the DFR pre-fault data and comparison with the files obtained from primary and backup relay indicated that the wiring of the B-phase was inadvertently inverted thus resulting in 180 degrees

shift (Fig. 4). Angle difference in the pre-fault should be 120 degrees not -60. What made this harder to spot, for this particular line, was that only phases A, B, and N were monitored. Benefits of having both relay and DFR data integrated into the same repository and easily accessible with an universal event viewer quickly helped to confirm the wiring problem. This example also prompted review of the monitoring policy checking it against NERC recommendations. The problem of data validation has surfaced and now different approaches to make sure all the recorded data are automatically validated are being explored.

V. USE OF CIRCUIT BREAKER RECORDERS

This section discusses adding circuit breaker monitoring to existing DFR and DPR setup. For this purpose a new device called Circuit Breaker Recorder (CBR) was designed and demonstrated in the filed.

A. Monitoring Circuit Breaker Control Circuit

The concept is to provide continuous monitoring and event based recording for (open/close) events inside the control circuit of a circuit breakers. Table III shows input signals of interests for the circuit breaker (CB) monitoring.

TABLE III

CIRCUIT BREAKER RECORDER: 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

It is necessary to provide a sufficient set of monitoring points inside of 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, X/Y coil signals allow taking a snapshot of the “health “ of the breaker every time it operates (Fig. 5).

Initial evaluation was performed in a training facility with a circuit breaker used to train technicians. All of the monitoring signals other than phase currents were wired and the tested breaker was operated. Several open/close records were produced and downloaded before going to the field.

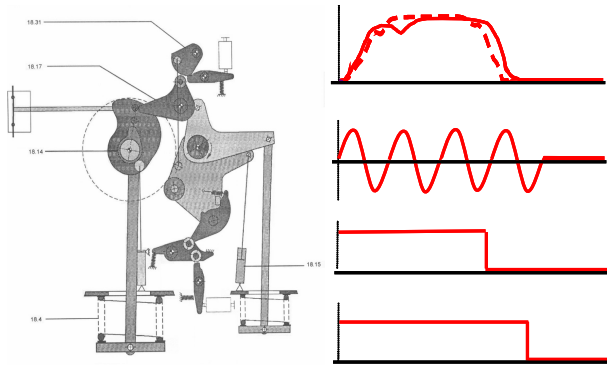


Fig. 5. Electric signals mapped to mechanical condition of CB

Additional input channels (both analog and status) are provided to enable monitoring of alarms, temperature, pressure etc. The CBR device does not have any output commands, just communication for data integration. The field setup is depicted in Fig. 6.

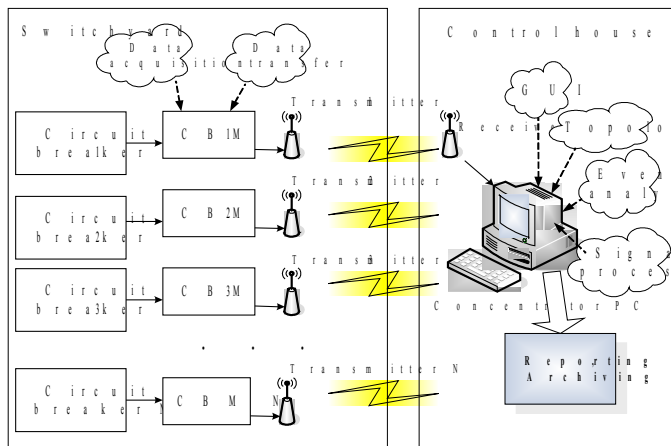


Fig. 6. Circuit breaker monitoring setup

B. Wireless Communication

The communication inside the switch-yard is implemented via wireless frequency hopping spread spectrum modems. The distance between Control Room and closest and furthest bus was 250ft and 600ft respectively. The communication system testing was completed without much trouble. It was noted that if needed, the master modem can be mounted outside above the obstacles with direct line-of-sight to monitored breakers. Since the CBRs do not have any control function, just the monitoring function they have been identified as “non-critical” assets per NERC cyber security recommendations.

The evaluation of wireless channels was performed in the field by having the new device next to to the circuit breaker control cabinet, while the computer with master modem was inside the Control Room. Please refer to Fig. 7 and 8. An additional challenge to the evaluation was the fact that the Control Room resides behind the

big transformer blocking the line-of-sight for some breakers.



Fig. 7. The CBR device next to the open CB cabinet

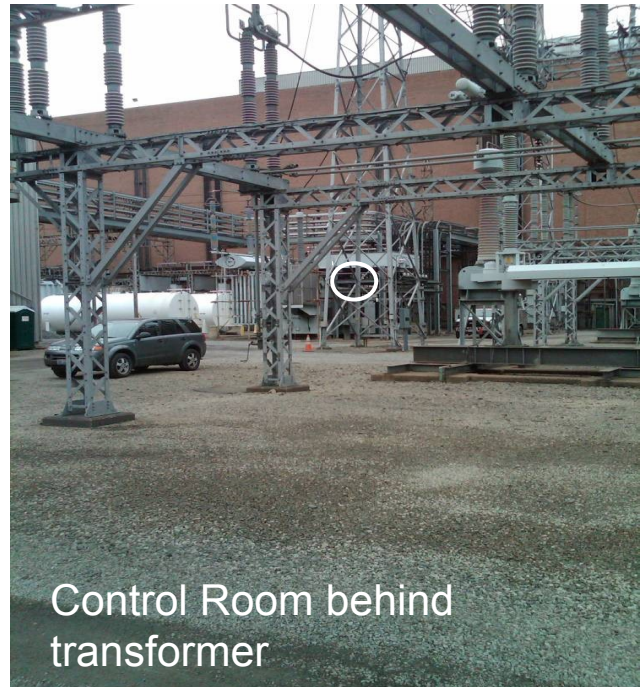


Fig. 8. Look from the bus towards the Control Room

C. CBR Data Analysis

A prudent approach is to keep a set of good reference cases that can be used as a baseline for verifying proper open/close operation of the breaker in question. It is critical to understand both the signal levels and even more so the signal timings as they directly correspond to condition of the breaker [12]. Features to look at are “trapezoidal” trip/close coil current shape, phase currents on/off, a/b contacts, voltage dip in DC, etc.

For the most part the analysis can be done by visual

inspection of the signals. A very useful tool is overlaying of 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. Fig. 9. depicts an example of trip coil current, one of the phase currents, dip in the DC supply, b and a contacts.

Having all of the CBR records in centralized repository allows for implementation of a breaker “health assessment” function and enables better forecast of possible failure. It is important to note that a historical data with records from all open/close breaker operations becomes a powerful tool in hands of maintenance and asset management groups as it allows them to make decisions on preventive maintenance based on analysis of historical data.

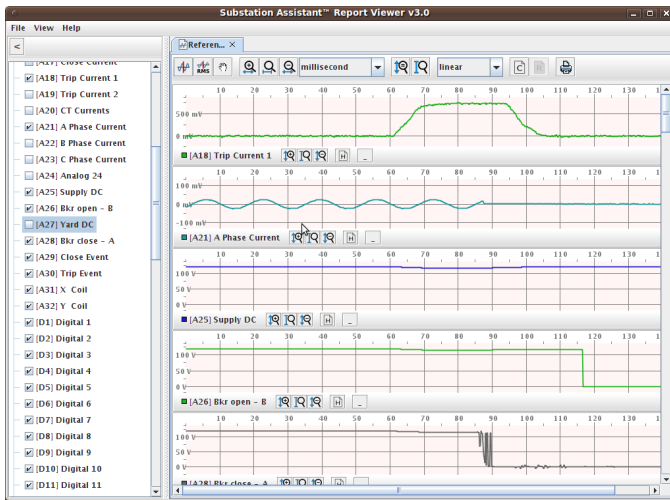


Fig. 9. Display for inspecting CB control circuit signals

VI. CONCLUSIONS

The paper discusses variety of practical challenges involved with substation IED data integration and automated analysis. The most important points can be observed:

- The requirements for the substation automated analysis are usually defined as a compromise of interests between many in-house stakeholders. It is important to understand that the requirements do change over time and that both the user and supplier for the solutions deal with a “moving target”. Being able to cope with the change management and provide a solution that can grow and adapt over time is the biggest challenge.
- There are several steps involved from the demonstration to the actual deployment. The paper illustrated gradual approach where the actual implementation has been tested using first the

simulated data, then an in-house testing with field data took place, and then, finally, the solution was deployed in the field.

- The experiences based on demonstration and deployment of the new device for circuit breaker monitoring called Circuit Breaker Recorder, illustrate the approach used to verify that the wireless communication system for transferring data coming from circuit breaker operations monitoring was intact. Several topics regarding wiring, communication gear placement, and CBR data analysis have been addressed.

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VIII. REFERENCES

- [1] M. Kezunovic, T. Popovic, “*Substation Data Integration for Automated Data Analysis Systems*”, IEEE PES 2007 General Meeting, Tampa, Florida, June 2007
- [2] *NERC Standard, Protection and Control, PRC-002-1 and PRC-018-1*, North American Electric Reliability Corp., 2006-2007
- [3] *NERC Standard, Cyber Security, CIP-002 through CIP-009*, North American Electric Reliability Corp., 2008.
- [4] *IEEE Standard Common Format for Transient Data Exchange*, IEEE Standard C37.111-1999, 1999.
- [5] *IEEE Recommended Practice for Naming Time Sequence Data Files*, IEEE PC37.232-2007, 2007.
- [6] *IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines*, IEEE Standard C37.114-2004, 2004.
- [7] Global Positioning System, Wikipedia, [online]: http://en.wikipedia.org/wiki/Global_Positioning_System
- [8] Substation Assistant™: “*Data Integration and Automated Analysis*”, [online]: <http://www.tli-inc.com>
- [9] Alternative Transient Program [online]: <http://www.emtp.org>
- [10] MATLAB™ [online]: <http://www.mathworks.com>
- [11] J. G. Webster, et al., *Wiley Encyclopedia of Electrical and Electronics Engineering*, A Wiley-Interscience Publications, John Wiley and Sons, Inc., 1999.
- [12] M. Kezunović, Z. Ren, G. Latiško, D.R. Sevcik, J. Lucey, W. Cook, E. Koch, “Automated Monitoring and Analysis of Circuit Breaker Operation,” IEEE Transactions on Power Delivery, Vol. 20, No. 3, pp 1910-1918, July 2005.