# Substation Data Integration for Automated Data Analysis Systems

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*Abstract* — **The paper discusses a concept of substation data integration for implementation of new automated analysis functions. Proper data integration is the main requirement to enable automation of the analysis and its future extensions. The integrated data concept is making the whole solution transparent to adding new types or product versions of IEDs, as well as new analysis functions.**

**There are several types of modern IEDs used in today's substations. Different file formats and data collection strategies are implemented by different vendors. The paper addresses the issue of integrating IED data recorded by different IED types and then focuses on how to facilitate the use the integrated data. Several new analysis functions can be performed on the collected IED data and the results of the analysis can serve different groups of utility users.**

**The paper introduces examples of automated analysis functions configured using the proposed concept for integration of IED data. The solution is open for adding new analysis functions that can utilize both the integrated IED data and the processing (analysis) results from other automated analysis functions.**

**The analysis functions, system configuration, and the whole concept of data integration are evaluated using digital power system simulator.**

*Index Terms* — **electromagnetic transient analysis, power system data integration, power system faults, power system measurements, power system monitoring, substation measurements, digital simulator.**

## I. Introduction

Modern substations are equipped with different types of intelligent electronic devices (IEDs) and most of these devices provide features for recording data. Processing the substation data and performing an automated analysis is the key for maintaining reliable system operation and speeding up the system restoration in cases of fault disturbances. Several types of IEDs together with their legacy software packages are primarily used to collect the substation data measurements [1]. Next level of substation data utilization is to apply existing or new analysis functions that perform automated processing of data collected by IEDs. Most of the existing analysis functions are device type specific and typically provided by device vendors. Being "locked in" to the functions tightly related to specific IED type or a vendor can sometimes be a obstacle in getting the bigger picture. This paper discusses a concept of substation data integration in order to enable multiple data analysis functions that are not necessarily device or vendor specific. Good examples of such functions are: universal digital fault recorder data analysis, circuit breaker monitor data analysis, digital relay data analysis etc. In addition, some functions need more than IED specific data and rely on the data coming from different types of IEDs as well as on the calculated data generated by other analysis programs.

New trends in substation automation propose use of advanced technologies that conform to new standards such as IEC 61850, IEC 61970, IEC 61968 [2,3,4]. These new standards define the communication, data collection, and substation configuration description. Utilization of the new standards should allow transparent use of IEDs in future applications.

The concept of data integration presented in this paper is aimed at enabling and automating the analysis of substation data [5]. First part of the paper focuses on substation data integration and its effects to analysis functions. Examples of analysis functions are described next. An example setup that utilizes integrated data and enables multiple analysis functions is described and evaluated using digital simulators.

## II. Background

The utilities employ different IEDs to monitor and control state of the electric power system and its elements. Typically, IED data records are kept in IEDs memory in the field and downloaded manually when needed or the data are uploaded to a dedicated computer, using vendors specific software. The viewing, analysis and classification of IED records are typically performed manually.

### A. Problems in existing IED data collection

Main problems related to data integration in existing IED systems are summarized as follows:

1. IED data records cannot be efficiently analyzed manually due to an overwhelming number of records obtained even in a moderately sized power system.
2. Use of different vendor specific programs increases training costs since software packages from different vendors have distinctively different features, as well as the look and feel.
3. Slow response (manual data analysis takes time) is an impediment if several records supplied by different IEDs for the same event must be uploaded and analyzed.

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4. Highly-skilled people devote a lot of time to routine tasks because most of the records may just confirm the proper operation of the equipment being monitored.
5. Non-selectivity (for example, IED data records are not event prioritized) is an issue if the operator must sort out the records for the analysis purposes.
6. Inefficient data archival and retrieval due to rather primitive means of storing and retrieving the data.
7. Lack of ability to integrate data coming from different IED types and models is evident when one attempts to integrate the different IED systems and services.

### *B. Moving toward integrated solutions*

First big step towards integration of substation data was the introduction of standardized data formats such as COMTRADE file format [6]. IED vendors are gradually accepting use of COMTRADE thus opening a door for easier data integration. Most of the vendors are still keeping their own native IED file formats, developing new ones and just providing additional utility programs or commands for exporting data in COMTRADE file format. Unfortunately, this export-to-COMTRADE feature, in most cases, is not configurable for automated operation. Additional issue is that the COMTRADE format specification allows freedom, to some extent, on how to provide information inside the files. This leads to situations where different software packages supporting COMTRADE file format cannot exchange data among themselves due to the lack of standardized descriptions of the files and signals inside. In addition to the original COMTRADE standard specification [6], there are the latest IEEE revision [7] and IEC version [8]. Having three versions in wide use increases a possibility not to be able to exchange IED data among different types of software packages due to inconsistencies between different versions.

One step further was the introduction of the standardized IEEE file naming convention for the time sequence data [9]. The proposed convention defines coded schema for naming the data files. Such file names can enable easier handling of large volume of files as well as unique file identification since the file name should contain unique information about the event: date, time, station, company, duration, location etc. Benefits of using this standardized file naming schema should encourage IED and related software vendors to provide the support, which is not a common feature today. There is still a lack of a standardized approach to communication protocols for IEDs and convention for providing information on parameters that describe system objects (signals and associated equipment) monitored by IEDs in substations.

Having a standardized communication protocols would allow much easier integration of IED systems and enable interchangeability of one type of IEDs with another of same type. Future IED systems may utilize standards like the one recently proposed by IEC [2]. Currently, a common approach is to use custom software provided by vendors. Vendor software should be configurable to automatically collect IED data files and make them accessible through corporate network, which is not a common feature today.

The solution described in this paper defines framework for data integration that allows automated IED data analysis. Preferably, all the IED data should be automatically converted into uniform file format utilizing a combination of vendor-based and custom developed software modules.

## III. Data Integration

Several IEDs may be used to collect the measurements in today's substations: digital fault recorders (DFRs), digital protective relays (DPRs), PQ meters, circuit breaker monitors (CBMs), remote terminal units (RTUs), sequence of event recorders (SERs), programmable logic controllers (PLCs), etc. Originally, most of these devices were designed and made with a very specific, often limited, data recording function in mind. The technological progress turns the IEDs into more sophisticated devices with more new capabilities. The crucial improvements include: more memory, better connectivity, and higher quality of data recording. These improvements enable adding new functionality, primarily related to automated processing and analysis of IED-recorded data [10,11].

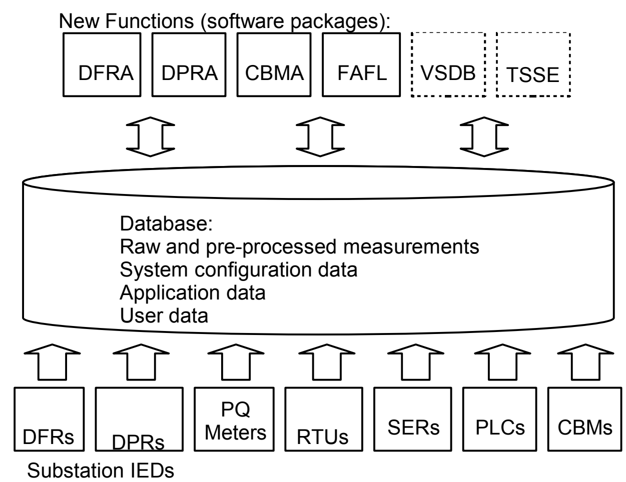


Fig. 1. IED data integration enables multiple analysis functions

The concept of adding new analysis functions to existing substation IED systems is given in Fig. 1. Major assumption and requirement to make this concept possible is substation data integration where the IED data are automatically collected and integrated into a substation data database.

Examples of new functions as shown in Fig 1 are automated analysis of DFR data (DFRA), DPR data (DPRA), circuit breaker monitor data (CBMA), as well as system-wide fault analysis with fault location function (FAFL). The application data includes both the maintenance/settings data and the IED output data. The output data from some applications may be an input for the others. For example, system-wide fault analysis may look at the analysis results coming from applications such as DFRA, DPRA, and CBMA.

Also, other functions besides the ones described in this paper may be implemented. For example: verification and validation of substation data (VSDB)[12], two stage state estimator (TSSE) [13], etc.

Automated collection of IED data can be done utilizing IED vendor legacy software packages or by direct access to IED's communication resources. The first approach is less involved and it is recommended since the standard communication protocols have not been widely accepted and/or implemented yet. All the IED-recorded data is meant to be converted to selected standard data format such as COMTRADE [7,8]. The file repository in the database should utilize standardized file naming convention [9]. It is most likely that the actual file repository integration will require combination of vendor-based and custom developed software modules in order to make sure that the records comply with the selected data format and naming standards.

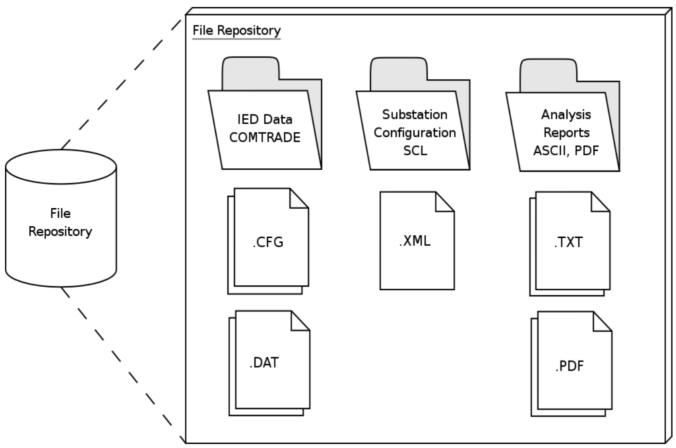


Fig. 2. File repository structure (concept)

Besides the IED data, the database has to contain system configuration data, which describe: 1) system components and their relationship (i.e. lines, buses, circuit breakers, switches, relays, CTs, VTs, etc.); 2) IED configuration and map IED channel assignments and calibration to specific system components (line/bus voltages, line currents, status signals). The system configuration data enables automated IED data conversion into standard formats and integration into the database thus making the data available for new functions (software applications).

The result of substation data integration is a database with file repository (Fig. 2.). The file repository should contain:

1. IED data (COMTRADE with proper file naming),
2. Substation configuration descriptions (described in Substation Configuration Language - SCL [2]),
3. Analysis reports (generated by different functions).

## IV. Analysis Applications

Automated analysis functions using data recorded by different substation IEDs may be identified as substation-wide or system-wide. Several of these functions are automated and event-driven. The device specific analysis functions should use the integrated data from the repository so that the vendor and model specifics do not affect the implementation. The integration of different analysis functions may be provided through a database utilizing unified data and report formats. The analysis functions at all levels of data processing (switchyard, substation, system-wide) should exchange information through the database.

The following are examples of automated analysis functions:

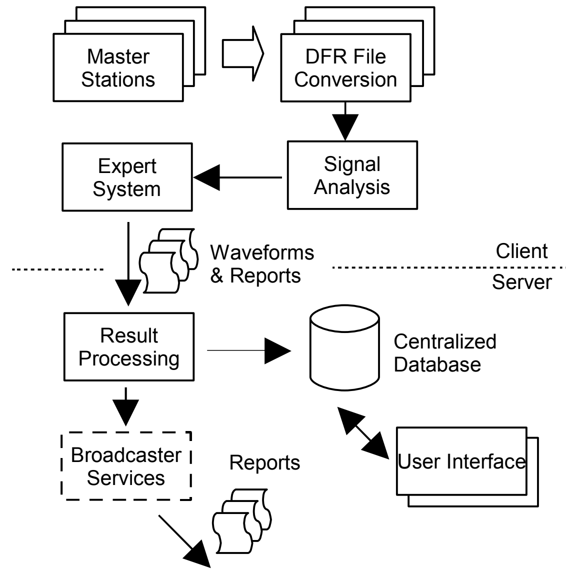


Fig. 3. DFRA functional diagram

*Digital Fault Recorder Data Analysis (DFRA)* is an application that conducts automated analysis of fault records captured by digital fault recorders (DFRs) and disseminates event reports (Fig. 3). Event analysis has the following goals [14]: 1) Detection and classification of faults and disturbances; 2) Verification of the protection system operation; 3) Verification of circuit breaker operation; 4) Calculation of fault location. This function automatically provides fault and disturbance data and analysis reports dramatically reducing the time needed for understanding the fault and expediting power system restoration.

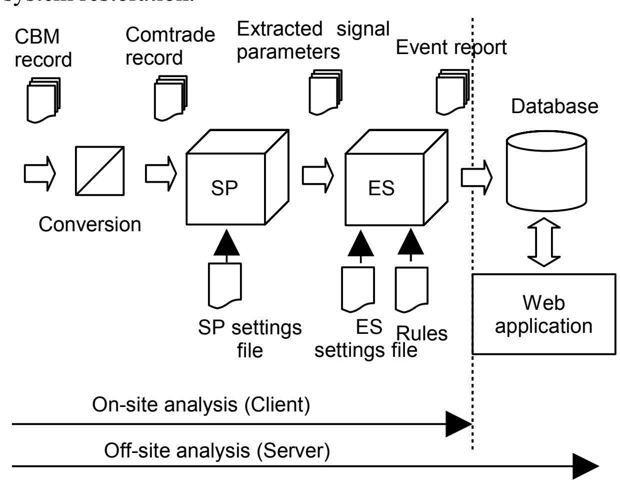


Fig. 4. CBMA functional diagram

*Circuit Breaker Monitor Data Analysis (CBMA)* evaluates performance of the circuit breaker (CB) operation based on the analysis of data taken from the CB control circuitry [15]. It requires input data in COMTRADE file format. At the end of processing, it gives a report in an ASCII text file format that contains list of circuit breaker operating problems as well as recommendations how the detected problems can be solved. It helps in CB maintenance as well as in predicting possible CB failures. The function provides lots of details related to CB operations that can be used in the upper level analysis functions.

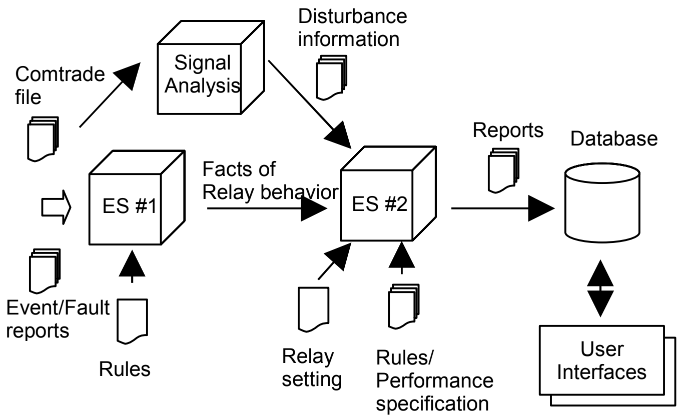


Fig. 5. DPRA functional diagram

*Digital Protection Relay Data Analysis (DPRA)* performs several analysis steps such as [16]: 1) Consistency check of the data in various relay files. The check is performed by comparison among osillography file, fault report and event report; 2) Verification of correctness of the data obtained from various relay files, which is done by comparing the reference data contained in the osillography file and the fault report; 3) Feeding the analysis results to another analysis functions such as Fault Analysis and Fault Location (FAFL), as described next.

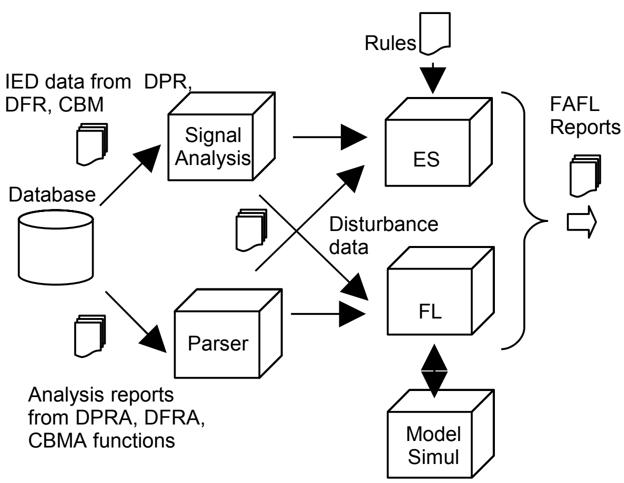


Fig. 6. FAFL functional diagram

*Fault Analysis Including Fault Location (FAFL)* includes the following [17,18]: 1) A novel algorithm for fault location. This algorithm requires data from several IEDs as well as the correct switching state of each substation at the moment of the fault; 2) Fault analysis which is partially based on processing results obtained from device specific applications such as DFRA and CBMA; 3) Local as well as system wide analysis of the faults. This module is intended to work as a system-wide analysis module and it uses data gathered from several IED types as well as calculated data and/or reports from other functional modules. A report from this function enables user to instantly focus on possible causes of the fault and the means for their elimination.

All of the presented analysis functions were originally developed independently and require customization to split data integration functionality (data conversion, file naming) and analysis functions (signal processing, expert system, report generation) into separate modules.

## V. Configuration Data

It is very important to distinguish between integration of data and integration of functions. Data integration has to include not only integration of all the IED recorded data, but also system configuration data and component descriptions. To enable automated analysis, the IED data collected in substations needs to be matched against the power system configuration and components. The system configuration has to be retrievable for any given time-stamp (extracted from the IED data). Power utilities have their system data entered in different databases but they rarely have interchangeability of the system configuration data between different applications. Keeping all the configuration data properly matched to the power system model and updated in different databases and applications is a major challenge.

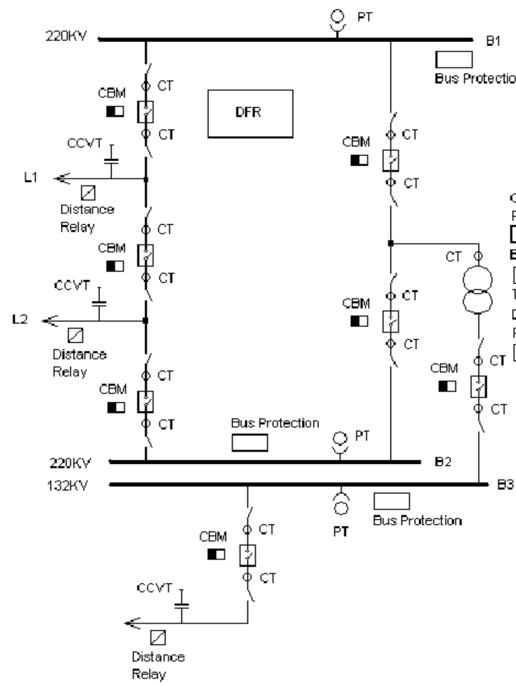


Fig. 7. Example substation configuration

An example of a simple substation one-line diagram is given in Fig. 7. In this example, one can identify several different substation components and different types of IEDs. Each component has to be fully described, placed in the system topology, and characterized with its parameters as well as its relationship to the IEDs that monitor its signals. For example, line L1 should be described as a line going from one substation to another (both ends of the line should be defined), with specified length, line impedances, related signals being monitored by the distance relay and DFR, rated bus voltage, other components attached to it such as CTs, VTs, circuit breakers and their CBMs, then corresponding description of the protection schema on this line, communication signals, etc.

Only a full description of substation and power system configuration will enable full integration of both data and functions. Power system configuration data is typically stored in different databases. Examples are custom databases developed by IT groups in power utilities or configuration data for short circuit study programs.

As mentioned before, additional requirement for handling the system configuration data is to keep history of all the changes. System configuration do change over time and it is very important to be able to restore system configuration data for any given time stamp from past. Keeping IED data in a database without knowing corresponding configuration and IED settings may make such a database useless for the use in automated analysis.

## VI. Example Solution

An example solution that integrates described analysis functions DFRA, DPRA, and CBMA has been configured and evaluated in lab and field environments. The IED configuration is depicted in Fig. 8. The figure represents one end of a transmission line in 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 monitors line voltages and currents as well as the status signals such as relay trip, breaker auxiliary, and carrier send/receive;
- DPR monitors line voltages and currents, digital status signals related to protective relaying function: trip, carrier send/receive, also all the external/internal status signals of the protective relay;
- CBM monitors line currents going through the circuit breaker, a/b contacts, X/Y coils, DC power supply, trip command.

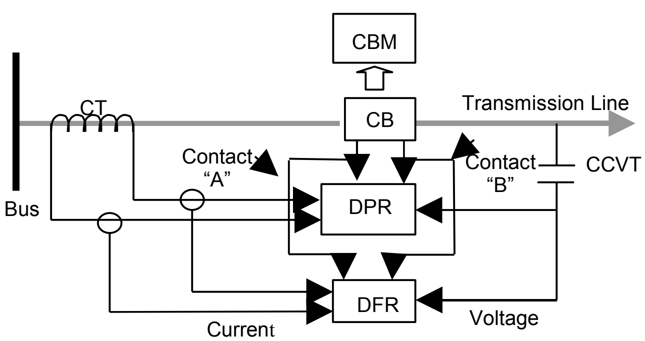


Fig. 8. Example IED configuration on a single line

Generally, a DFR would monitor most of these signals for all the lines (or at least the most important ones) and give the most 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 can provide much more details on its own operation (time-stamped log of all the status changes of internal/external elements). A CBM in this configuration would monitor all the signals related to a particular circuit breaker. Similarly to the DPR monitoring, CBM would provide much more details on 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 enable waveform alignment and comparison. In this particular example, it is assumed that a substation PC exists and that all the IEDs are connected and configured for automatic data transfer to it. In addition, all substation PCs can be connected to a main server located in central offices. The actual evaluation is done using digital simulator.

Now we discuss scenario and operation of the new automated analysis applications functions in the case of an event/fault on the transmission line depicted in Fig. 8.

### *A. DFRA operation*

An event on any of the lines in a substation may trigger a DFR recording, which are automatically transported to substation PC. This is typically done utilizing DFR master station software packages in auto-poll or auto-call configuration. DPRA function is triggered by occurrence of a new DFR file being deposited in the substation PC folder designated as the incoming folder. DFRA function opens the new DFR file, converts it to COMTRADE file format, selects the transmission line with signals showing the most prominent disturbance and then automatically performs the analysis of all the monitored signals related to that line. The DFRA can give some indications on how well or bad DPR and/or CB performed, but it cannot give a detailed comprehensive insight into DPR and CB operations and internal states.

### *B. DPRA operation*

A DPR would typically trigger only on the events related to the transmission line it is tied to. When event/fault occurs, a DPR performs its primary function - protection, but it also executes its monitoring and analysis functions and provides a set of relay files related to the event. The files are downloaded by substation PC and made available to DPRA software function, which then extracts disturbance information and combines it with the relay setting to determine a hypothesis of expected relay behavior. DPRA also identifies facts of the relay's actual behavior and then compares it with the hypothesis. The result of the analysis is stored into validation and diagnosis report.

### *C. CBMA operation*

Case when an event includes CB operation causes CBM to take a snapshot of all the monitored signals on the breaker. CBM then sends the event record to the substation PC where the record becomes available for CBMA functional module. CBMA converts the data into COMTRADE file, and performs extensive analysis on the waveforms. The analysis produces detailed report tied to the specific CB.

The IED test data is generated in a lab setup utilizing digital simulator (Fig. 9.). Digital simulator tools were used to simulate different test scenarios [19]. ATP power system model is used to generate test waveforms, which are later applied to IEDs inputs (DFR, DPRs, and CBMs) simultaneously to simulate a power system event as it would be "seen" as if the IEDs were installed in a substation.

Each simulated event triggers recording operation of multiple IEDs. The recorded data is downloaded and integrated into the data repository by converting and properly file naming the files. The occurrence of new files in the repository initiate automated analysis functions. Finally the analysis reports associated with simulated events appear in the report repository.

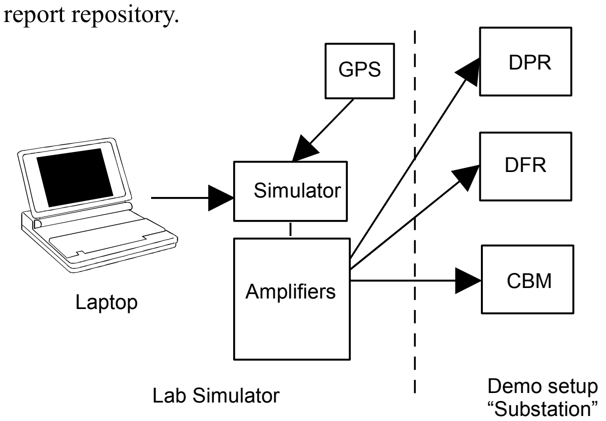


Fig. 9. Digital simulator is used to evaluate integrated solution

## VII. Conclusions

The paper focuses on the substation data integration as the main requirement for implementation of automated analysis functions. The proper data integration also allows easy integration of multiple analysis functions and their coordination. A database is used as connecting point between different analysis functions. Keeping all the records in an unified data format with proper event file naming makes system transparent and maintainable when new IEDs , or even when new analysis functions, are being added. The importance of maintaining the proper power system configuration data is addressed as well.

New analysis functions are presented and an example solution that combines these functions is described. Evaluation of the example configuration is done utilizing digital simulator tools. Digital simulator can be very effective for evaluation of substation data analysis functions. The simulator provides simulated data for different test scenarios (different fault types, locations, etc.) thus makes a great tool when the analysis functions are evaluated individually or as a part of a system solution.

The different utilities may have different needs and utilize different IED types, models, and communication infrastructure. The concept of integrating multiple analysis functions through the integration of data allows use of different IEDs and variety of combinations of analysis functions, thus makes it possible to create a custom solution that conforms to specific utility requirements.

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## IX. Biographies

**Mladen Kezunovic** (S’77, M’80, SM’85, F’99) received his Dipl. Ing. Degree from the University of Sarajevo, the MS and PhD degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively.

He has been with Texas A&M University since 1987 where he is the Eugene E. Webb Professor and Site Director of Power Systems Engineering Research Center (PSerc), an NSF I/UCRC.. His main research interests are digital simulators and simulation methods for equipment evaluation and testing as well as application of intelligent methods to power system control, protection and monitoring. Dr. Kezunovic is a registered professional engineer in Texas and a Fellow of the IEEE.

**Tomo Popovic** (M’99, SM'06) received his BS degree in electrical engineering in 1994 from University of Novi Sad, Serbia and his MS degree from Texas A&M University, USA.

He has been with Test Laboratories International Inc. since 1998 where he is a development engineer. His prior positions were with NIS-GAS, part of Petroleum Industry of Serbia, and University of Novi Sad, both in Novi Sad, Serbia. His main professional interest is developing and implementing software and hardware solutions for industrial applications, especially in the field of electric power system engineering: analysis of fault records, transient testing of protective relays and digital simulators. Mr. Popovic is Senior Member of IEEE.