Automated Analysis Using IED-Recorded Data: Implementation and Integration

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***Abstract* — The paper discusses collection and utilization of IED-recorded substation data in an automatic way. It focuses on adding new automated functions built on the top of the substation IED database. There are several types of modern IEDs used in today's substations. Different file formats and data collection strategies are provided by different vendors. The paper addresses the issue of integrating IED data collected by different IED types and then focuses on how to use the integrated substation data.**

Several new analysis functions can be performed on the collected IED data and the results of the analysis can serve different groups of users. The paper introduces four newly created and implemented analysis functions. The new functions include automated analysis of digital fault recorder data, digital protective relay data, and circuit breaker monitor data. In addition, a high-level analysis function that performs system-wide fault analysis and fault location is described. This high-level function utilizes IED data from different IEDs that can be collected from different substations as well as the data coming from other analysis functions.

An example scenario where all four functions have been implemented is demonstrated at the end.

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

I. Introduction

HANDLING 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. Good examples are: 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 programs.

It is important to note that the analysis applications have a key role in accessing and handling the substation data. There are generally three groups of applications: measurement monitoring/tracking, substation level analysis, and system-wide analysis. 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 new concept of data integration and information exchange primarily aimed at automating the analysis of substation data [5].

The paper addresses several issues: 1) how to interface a new application to the existing legacy systems to enable upgrading of the existing systems since complete equipment replacement is not always feasible; 2) how to use data coming from different types of IEDs such as digital fault recorders, digital relays, circuit breaker monitors in a single application; 3) how to use data outputs from one group of programs as an input to another, for example, how to broader fault analysis and fault location calculation based on results coming from IED specific analysis programs; 4) how to customize existing software solutions to work in the environment defined by standards such as IEC 61850, IEC 61970, IEC 61968; 5) how to define new applications such as digital relay data analysis and fault analysis including fault location. All the discussions are supported by examples of application implementations.

II. Background

Several IEDs may be used to collect the data 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 collection function in mind. However, with the technological progress, all these IEDs evolved into more and 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 [6].

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

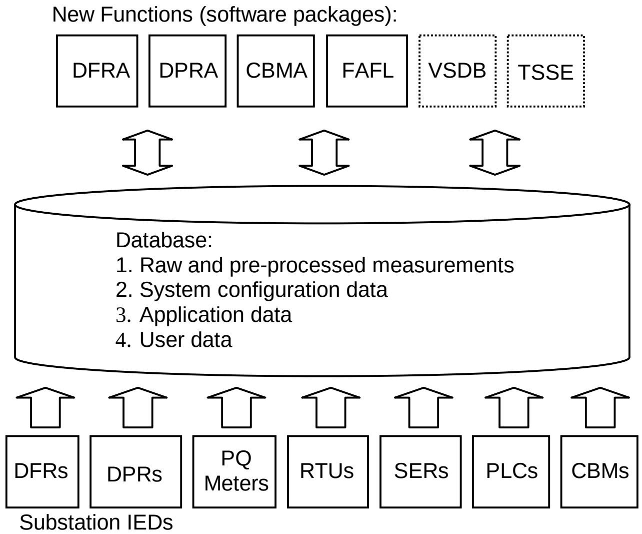

Fig. 1. Adding new software functions over substation IED data

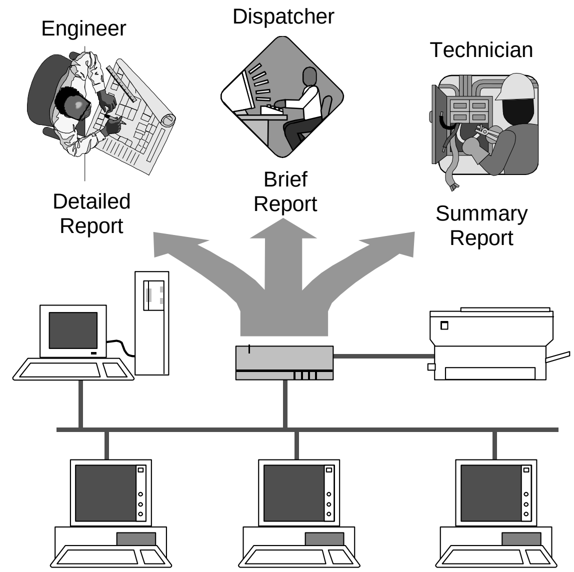

Fig. 2. Delivering customized electronic and paper reports

Automated collection of the 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 isrecommended 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 standard data format such as Comtrade [7,8]. The file repository in the database should utilize standardized file naming convention [9].

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).

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. Please note that 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.

Please note that other functions may be implemented besides the ones described in this paper, for example: verification and validation of substation data (VSDB)[10], two stage state estimator (TSSE) [11], etc.

The proposed concept also enables different types of users to access the database utilizing customized user interfaces. Different users, belonging to different groups may have a need to access different substation data and analysis functions. Also, the level of details may also differ.

Customized electronic and paper reports can be generated depending on the user needs (Fig. 2.). Utilizing new web technologies [12,13], user access to the database should be implemented as web-based application meeting particular needs as well as the privileges. Fig. 2. illustrates an example where the users can belong even to the same user group but may have different need and/or privileges.

III. New Functions: Integration and Implementation

Several new functions can be implemented and integrated into a substation data analysis system. Most of these functions can be implemented as automated and event-driven. Depending on the data range, new functions can be divided as follows:

- **IED specific.** Typically, these functions work on specific IED type data such as DFR, DPR, SER, etc.
- **Combined IED**. The function is related to integrated data coming from several IEDs.
- **System-wide**. The function is executed over the data that can be collected in several substations, by different IED types.

In the case of new functions, integrated data includes: raw IED data, pre-processed IED data (i.e. IED data converted form legacy to standardized formats) as well as the processed data (i.e. output data from other functions).

The main requirement for enabling integration of functions is providing effective data integration and enabling smooth information exchange. This requirement must be satisfied at all levels of data processing (switchyard, substation, system-wide).

A. DFRA function description

The main goal of this analysis is to detect the fault, identify the fault type, and assess the performance of relays, communication schemes and circuit breakers involved in the fault clearing [14]. The idea is not new and different versions of this function have been implemented [15].

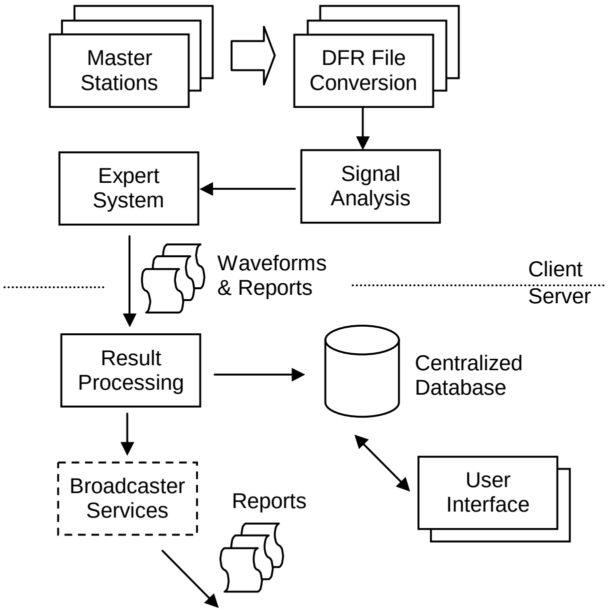

Fig. 3. DFRA functional diagram

A solution that has been implemented utilizes IT technology embedded with the automated fault analysis to provide an integrated solution. The design requirement for this solution is centered on the need to connect DFR Master Stations (MS) located in multiple service centers using the Internet technology. In addition, each service center has a variety of MS programs produced by different vendors, each connected to several DFRs from related vendor. The solution is shown in Fig. 3.

The analysis enables reaching the following conclusions:

- Fault type and location;
- Performance of relays, communication channels and circuit breakers;
- Occurrence of ferroresonance conditions and auto-reclosing sequences.

The use a broadcasting features (e-mail, fax, printer) as well as web-based GUI with the database allows the following enhanced user functions:

- Retrieving the data and reports using web browser services
- Disseminating the analysis results through fax modem, pager, and email broadcast services
- Maintaining the database and user interface settings through straightforward means

This solution has shown some major benefits when compared with the traditional approaches: centralized database; easy integration with other automated functions; universal user interfacing and analysis regardless of DFR type/vendor.

B. CBMA function description

The main objective is to analyze circuit breaker (CB) operation performance each time it operates. Detailed analysis of the breaker operation is enabled by monitoring of additional control signals related to CBs and with an extensive rule-based expert system [16].

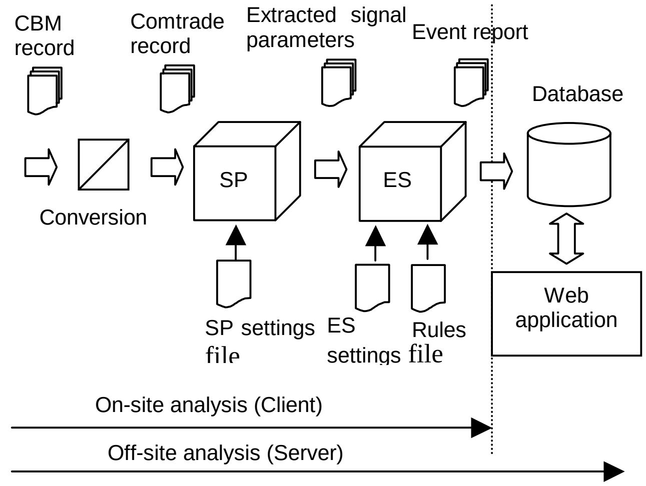

Fig. 4. CBMA functional diagram

This analysis also identifies several breaker operation features pointing to potential failures in the future.

The system architecture and basic software modules are show in Fig. 4. The system architecture is typically split between two locations: the substation where data are recorded during breaker testing and the central repository where data from all tested breakers are gathered.

In the particular case, Rochester recorder is used as a CBM device for monitoring the CBs. After the data format conversion, the analysis software performs signal processing (SP) in order to extract several features and parameters relevant to the operation of CBs. This module extracts pertinent signal parameters from recorded signals using advanced processing methods such as: wavelet analysis, Fourier analysis and digital filtering. The extracted parameters are then processed by a rule-based expert system (ES), which is a decision making system emulating reasoning of a human expert. Around one hundred rules are used in this particular solution.

The client part of the application is used on-site (in substations). The server application is installed in the centralized office and, in addition to the analysis, maintains the centralized database and provides an extensive web based user interface. The server is typically connected to the corporate intranet. There is an option to upload CBM files to the server from any computer connected to the company intranet. Web application (Fig. 5) enables easy manipulation of data and reports as well as additional tools for manual analysis by experts.

In the context of the extended fault analysis, the CB analysis can be triggered each time the relay or CBM initiate/detect an operation of the breaker. In that case, the CB monitoring system can provide additional details about the CB operation and can alert both protection engineers and maintenance crews about related details.

C. DPRA function description

Typical design of modern digital protective relays is based on a concept of functional elements. The elements handle inputs, outputs, protection, control, and pilot schemes.

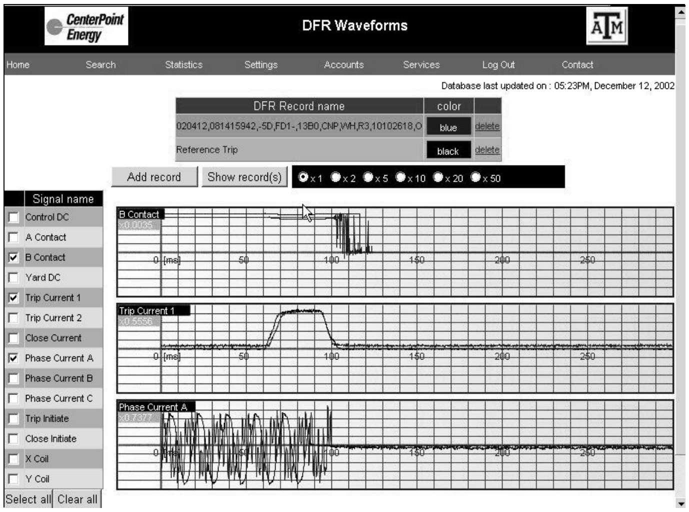

Fig. 5. CBMA web based user interface

The statuses and timing of each element are recorded in various reports and such relay files define external and internal operation behavior of relays. File formats and names of relay files and reports can vary from vendor to vendor. However, if generalized, each digital protective relay generates the following files: event/fault reports, oscillography file, and setting file [17].

Event/fault report files contain information on fault type, fault location, phasor values of voltages and currents in pre- and fault-periods as calculated by the relay. These files also contain log of element status changes with time stamps and in chronological order so both the external operation and internal states can be observed. Oscillography contains samples both analog values (three-phase voltage and current signals) and digital status data corresponding to the relay elements. The oscillography file is in its nature similar to recordings obtained using DFRs, only in this case just the signals related to the protected circuit are being monitored. Setting file corresponds to the relay's configuration.

DPRA functional diagram is given in Fig. 6. The signal analysis is performed on Comtrade files in order to extract the disturbance information.

Based on the event/fault reports and Comtrade file, first stage of the expert system (ES #1) generates facts about relay behavior. Second stage (ES #2) looks at the disturbance information, then generates a hypothesis on desired relay behavior and compares it to the factual relay operation evaluated in the first stage.

As with the previous functions, both the analysis reports and data obtained from the relay are stored into the centralized database and made available for further use.

D. *FAFL function description*

FAFL function is a software module intended to work as a system-wide analysis [18,19]. It is executed as a higher-level function when compared to DFRA, DPRA, and CBMA. It uses the data collected from several IEDs and also data obtained from different substations.It is expected that such a functional software module is installed and executed on a server located in central offices.

FAFL software module accesses the data available in the centralized database (please refer to Fig. 7.). The execution is triggered by occurrences of new event produced by IED specific functions such as DPRA, DFRA, and CBMA. A time delay is allowed to allow that all the IED data is collected and all the analysis reports are available. Signal analysis extracts the disturbance data directly from the IED-recorded information, while the parser extracts the disturbance data from the reports previously generated by other functions. Please note that at this stage it is possible to use the data obtained from several substations (e.g. from both ends of a transmission line where the fault occurred).

A novel algorithm for fault location utilizes the disturbance data to calculate fault location [18]. Data obtained from different IEDs and different substations is properly aligned using event time-stamps. The algorithm also determines correct switching state of each substation at the moment of the fault. This information is used in the simulation model and simulation results are compared to IED data in order to precisely determine the fault location.

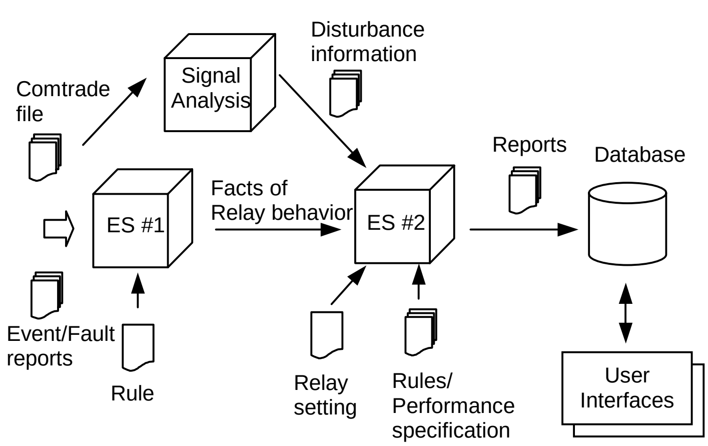

Fig. 6. DPRA functional diagram

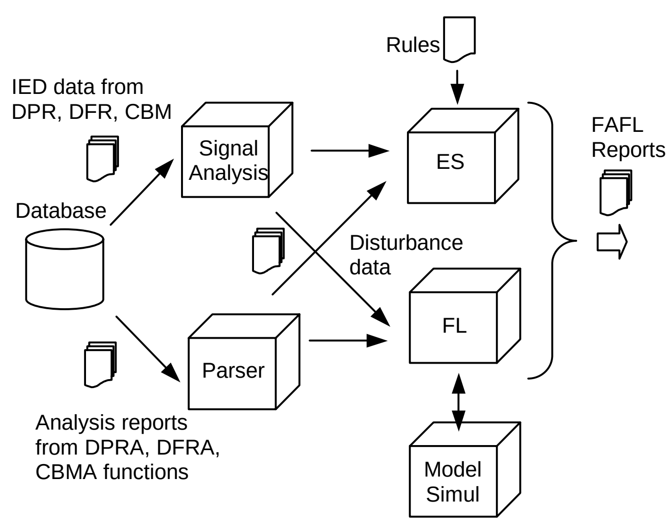

Fig. 7. FAFL functional diagram

Fault analysis incorporates results from the individual analysis modules into a comprehensive report. In addition, availability of the data obtained from several substations as well as the redundancy of data obtained from different IEDs in substations allow further validation and more detailed analysis.

A report from this function enables user to instantly focus on possible causes of the fault and the means for their elimination.

IV. Example Scenario

A. Configuration

An example IED configuration is depicted in Fig. 8. The figure displays one-line detail of a portion of a substation. The 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.

Generally, a DFR would monitor most of these signals for all the lines (or at least important ones) and give the most comprehensive overview of the signal changes for the whole substation.

Each protective relay monitors only signals related to it. A relay does not “see” the signals related to other system components, but the relay recording can provide much more details on its 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.

Please note that 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 are connected to a main server located in central offices.

B. Behavior of new functions

This section discusses scenario and operation of the new functions in the case of event/fault on the transmission line depicted in Fig. 8.

1) DFRA operation

Basically, an event on any of the lines in a substation may trigger a DFR recording.

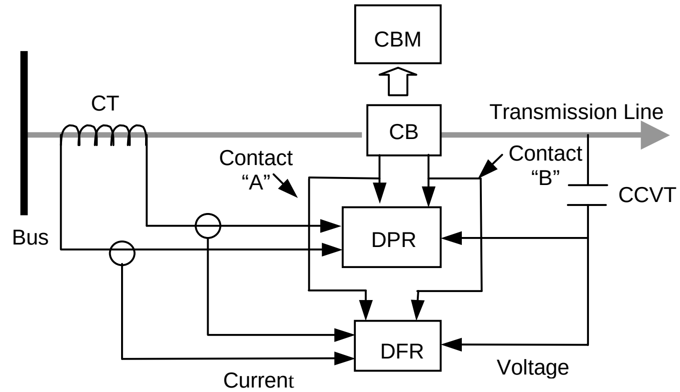

Fig. 8. Example IED configuration on a single line

DFR recordings 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 DFR incoming folder. DPRA function opens the new DFR file, converts it to Comtrade file format, selects the line with highest disturbance and then automatically performs the analysis of all the monitored signals related to that line. The DFRA analysis can give some indications on how well or bad DPR and/or CB performed, but it cannot give a detailed comprehensive insight on DPR and CB operations and internal states.

Both Comtrade file resulting from data format conversion and analysis report are stored in local database and also delivered to a server in a central office.

2) DPRA operation

A DPR would typically trigger only on the events related to the 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. DPRA then extracts disturbance information and combines it with the relay setting to determine a hypothesis of 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.

Similarly to DFRA function, both relay files and analysis report are stored in local database and also delivered to a server in a central office.

3) 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.

4) FAFL operation

FAFL function is a high-level software module and is expected to run on a server in central office.

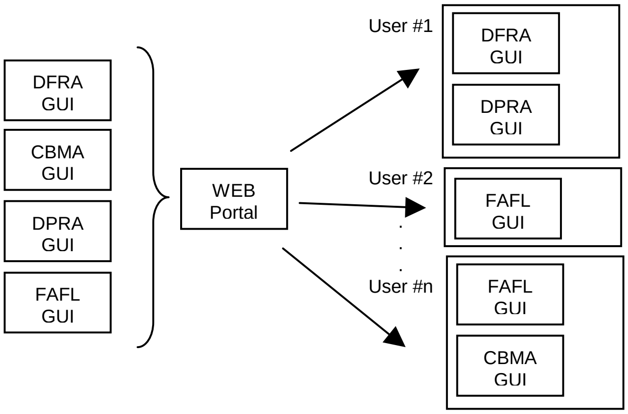

Fig. 9. Different GUI activated depending on user profile

The activation of the function is the most complicated since the function expects input data from multiple sources: 1) IED-recorded data coming from different types of devices and from different substations; 2) analysis reports generated by other low-level (in this case IED specific) functions executed in substations. Aligning time-stamps from different IED recordings as well as matching of the waveforms is used to determine which recordings relate to the same event. Therefore, proper and timely maintenance of the centralized database is crucial for FAFL function.

The input pre-processing has to determine when all possible related IED data is available and when the analysis and fault location can take place. The fault analysis will analyze IED data from multiple substations (typically two ends of a transmission line) taking into account the analysis results from low-level analysis functions such as DPRA, DFRA, and CBMA. Fault location would also check the results obtained from DFRA and DPRA and then perform sophisticated two end fault location algorithm. FAFL generates a comprehensive event report that is stored into centralized database and made available for dissemination and access.

All the IED data (both raw and processed) together with the analysis reports are stored in the database. The analysis reports can be automatically broadcast to selected users (user profile). User can browse the database via web portal that will activate different GUIs depending on the user profile (privileges, interests) as show in Fig. 9.

V. Conclusions

The paper introduces a new concept of utilizing the IED-recorded substation data in automated way. The concept assumes mixture of legacy solutions and newly developed functions. First step is to use the legacy software packages to automatically download IED data to the substation PC.

Once the IED data is available on the substation PC, database maintenance functions take the IED data in its native data formats, convert the data into Comtrade file format, store it into the database thus making the data available for users and other applications – new functions.

Several level of functionality can be implemented. The paper introduces four new functions: three of them being IED specific analysis functions (DFRA, CBMA, DPRA), and one of them being system-wide analysis function (FAFL).

The concept of the implementation and integration of new automated analysis functions is described through an example scenario. All of the presented functions have been implemented and tested on real substation data.

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