Requirements Specification for and Evaluation of an Automated Substation Monitoring System

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Summary: This paper presents functional requirements for the Automated Analysis Substation System (AASS) implemented at Texas A&M University, aimed at monitoring functions using data measured by multiple substation Intelligent Electronic Devices (IEDs). The implemented system is based on a new concept of data integration and information exchange where the data from several substation IEDs is integrated and information needed by various groups of utility users is extracted. Once fully implemented, this solution will provide both local and remote functions allowing further benefits to be drawn from the concept of substation data integration and information exchange.

Keywords: Substation Automation, Intelligent Electronic Devices, Protective Relays, Automated Fault Analysis, Fault Location, Modeling and simulation

INTRODUCTION

The process of substation automation can be defined as deployment of substation and feeder operating functions ranging from supervisory control and data acquisition (SCADA) and alarm processing to integrated volt/var control in order to optimize the management of capital assets and enhance operation and maintenance efficiencies with minimal human intervention [1]. This process is closely related to the substation integration – which by integration of monitoring, protection and control functions into a minimal number of platforms, aims at reduction of operating costs, redundant equipment and databases. Modern Intelligent Electronic Devices (IEDs) not only perform various control and protection functions but also monitor and record

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valuable information, both operational and nonoperational. Consequently, the new architecture of the substation automation systems is being based on integration of the IEDs, instead of the previously used RTUs .

The new substation automation system receives data from various devices such as Digital Protective Relays (DPRs), Digital Fault Recorders (DFRs), PQ Meters (PQMs) and other monitoring sensors and devices installed in the substation. With this variety of installed IEDs, several problems emerged. One of the most important problems is lack of data verification, both analog and digital, which can lead to serious errors in substation operations. Understanding current statuses of substation equipment (such as circuit breakers), load flows, location and type of faults, can be very difficult with unmatched sets of data.

This can greatly affect the capabilities of operators to monitor and control the substation and the whole system. Therefore, data verification should be one of the main requirements of automated substation monitoring systems.

The second problem in existing substation automation practices is related to the operators inability to efficiently extract required information. One of the reasons for this is the large quantity of data originating from IEDs. Data formats coming from different devices, such as waveform samples or event reports, are often different and not simple to compare. Some information contained within might be less important for particular group of users, but more significant for the others. Non comprehensive data acquisition can be an obstacle to the users drawing the conclusions about the mutual relationships between the data originating from different IEDs, as well between the data recorded at different time intervals from a single IED. Consequently, relevant information from IED recordings can stay obscured and hidden, leading to the limited understanding of conditions, operations and events in the substation and the system.

Finally, in order to maintain the substation equipment in best operating condition, without to much disruption in power supply to the users, Equipment Condition Monitoring (ECM) has to be used widely in the substation automation systems. Equipment availability and reliability can be improved by constantly tracking and monitoring various parameters of different substation devices, such are transformers and circuit breakers, which will minimize the maintenance cost and extend their exploitation time. Based on mentioned facts, it can be concluded that the goal of every successful substation automation design should enable full integration of ECM IEDs into the substation architecture.

The Automated Analysis Substation System (AASS) described in this paper, presents a unique solution to the problems mentioned above. It is a software solution, running permanently on concentrator PC installed locally in the substation. The AASS is based on a suite of software applications featuring functions for data verification, extraction and analysis, integrated by centralized graphical user interface. It features two original approaches to the process of data verification. The system performs the classification of extracted data and provides for customizable reports. Information such as switching sequences of circuit breakers (CB) and fault parameters are locally extracted from IEDs.

System enables for data archival and integration by implementing the substation database. Remote access to the data and analysis reports over the local/wide area network (LAN/WAN) is provided to the geographically dislocated users.

In the first section of the paper, the architecture of the system is described and then the functions for verification and analysis of data are elaborated. Database and user interfacing needs are presented at the end.

SYSTEM ARCHITECTURE

The implemented architecture of the Automated Analysis Substation System is displayed in Figure 0. The core of the system consists of eight applications performing the verification, extraction and analysis of substation data.

Generally, data verification performed by AASS applications can be done in two ways: first, by using the redundant measurements from different IEDs or by comparing the field acquired data with the simulated ones.

In current implementation, we assume that all acquired data are already available on the concentrator PC. Before the analysis starts, the software converts the data into the COMTRADE file format and renames the records according to the IEEE file naming convention [2], [3] .

Data are simulated using the substation data model defined in the Advanced Transient Program (ATP) [4]. We have opted for a fixed topology of an arbitrary substation, featuring breaker and a half scheme common in US utilities.

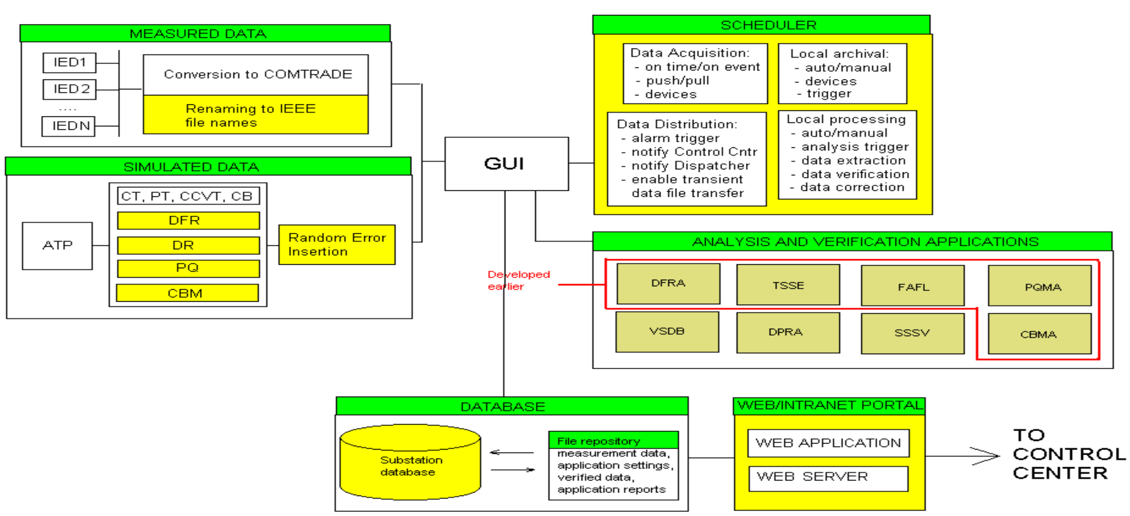

Figure 0 Automated Analysis Substation System Architecture

The model and the simulation software are embedded in the client application enabling users to set various parameters of the simulation, insert fault events and generate random data errors.

In current implementation, our system allows for simulation of DPR, DFR, PQ, CBM, data as well as currents and voltages measured by CTs, PTs and CCVTs. In the near future, we will integrate the digital relay model into the model of the substation which will enable simulation of the relay operations as well.

The centralized graphical user interface integrates all existing software modules enabling users interaction. User interface provides functions supporting simulation, acquisition and conversion of data. It features tool for graphical display of data. The tool is used to communicate with analysis and verification applications, scheduler, database and web application providing the online access.

One of the most important features of the system for automated analysis is the flexibility. Thanks to the scheduler and system design, user can remotely configure the way how the particular functions of the system are being performed. For example, user can select different options about how the data is acquired – whether the data is pushed by IEDs or pulled by concentrator PC, from which devices are data acquired, for what times or events. Apart from data acquisition, there are options for configuring data analysis applications, such as whether they are performed manually or automatically, what triggers the analysis process and other. Data archival and distribution modules provide options for configuring these two very important processes using the scheduler functionality.

The substation database supports archival and integration of all acquired and simulated data, such as samples of current and voltage waveforms recorded by different IEDs, digital status of circuit breakers, reports from DPRs, DFR recordings, PQ measurements etc.

The results of analysis and verification applications, contained as reports or sets of verified data, as well as application specific settings and other parameters, are also stored.

The web application with web server enables remote access to all information stored into the substation database. Using the serves side processing technology, users can queries the information according to the multiple criteria and see the results online.

FUNCTIONS FOR VERIFICATION AND ANALYSIS OF DATA

The functions for verification and analysis of substation data in the AASS are implemented as eight separate software application. Their goal is to enhance existing substation automation practices by using some new approaches and applying new algorithms to the problems of data processing and information extraction

Table 1 New Automated Analysis Functions

Function name	Inputs	Outputs	Description
Circuit breaker monitor data analysis (CBMA) [10]	Digital samples of signals from circuit breaker control circuitry in COMTRADE [2]file format	Report in an ASCII text file format containing list of circuit breaker operating problems as well as recommendations how the detected problems can be solved	Evaluates performance of the circuit breaker based on the analysis of data taken from the control circuitry
DFR data analysis (DFRA)] [7]	DFR records in COMTRADE file format	Report in an ASCII text file format containing results of detection and classification of faults and disturbances, verification of the correctness of the protection system operation and fault location calculation	Conducts automated analysis of fault records captured by digital fault recorders (DFRs) and disseminates event reports
Power quality meter data analysis (PQMA) [9]	PQ measurements	Report in an ASCII text file format containing results of event detection and classification, waveform characterization, equipment sensitivity study and fault location calculation	Power quality analysis and modeling
Two-Stage State Estimation (TSSE) [4][6]	Substation topology and measurements data	Report in an ASCII text file format containing the results of three estimation phases: First Stage State Estimator, Suspect Substations Identification, Second Stage State Estimation and Correction of Topology Errors	Detection and identification of the topology errors
Digital Protective Relay (DPRA) [8]	Digital Relay files in COMTRADE file format	Report in an ASCII text file format containing estimation of relay performances	Consistency checking of the data of various relay files. Correctness verification of the data of various relay files
Verification of switching sequences (VSSS)	Statuses of switching devices and substation topology	Report in an ASCII text file format containing the results of the analysis and verification	Determination of optimal switching sequence for each type of fault condition or load transfer operation. Verification of the switching sequences
Fault analysis including fault location (FAFL) [11]	Analysis results from CBMA and DPRA applications	Report in an ASCII text file format containing the results of the system wide fault analysis	It performs local as well as system wide analysis of the faults

In Table I the applications are listed together with the input and output data. Brief description of every application is given. Generally, the applications can be categorized in two groups, based on their functionalities. First group are status tracking applications and the other are applications for automated analysis.

The status tracking functions provide additional level in the process of data integration that enables verification of substation data. There are two functions for status tracking: Two-Stage State Estimation [4][6] and Substation Switching Sequence Verification.

Some of the automated functions can be identified as device specific applications that provide analysis of data collected by specific IEDs in substation, such as Digital Fault Recorder (DFR) [7], Digital Protective Relay (DPR) [8] , Power Quality Meter(PQM) [9], Circuit Breaker Monitor (CBM) [10] or Operator Meter. Other functions may be identified as substation-wide or even system-wide automated analysis applications. Examples are Fault Analysis including Fault Location (FAFL) [11] and Two-stage State Estimation [4][6].

SUBSTATION DATABASE

The design requirements for substation database are based on several factors. In order to define the required size and structure of the database, one must determine who are the users of the substation automation data, what is the nature of their application, what type of data they need, how often the data is required and what is the frequency of the update by each user. Since different user have different requirements, database will have to accommodate needs of all users - substation design engineers, protective relay engineers, dispatchers in the control centers etc.

Another significant factor influencing the requirements of the substation database is the existing data flow in the substation and the whole system. Namely, the substation database is used as a data warehouse for both operational and nonoperational data. Operational data is mostly collected and transferred by SCADA system. Consequently, the features of SCADA system will decide upon the features and performances of the data warehouse as well.

Many other important factors are affecting the database solution: the format and types of stored data, the ways how the data is synchronized, whether the data is pushed or pulled from IEDs into the database, the dynamics of data transitions and required flexibility regarding the topology.

Finally, required level of data security can have significant role when designing the substation data warehouse. Since substation database can contain data vital for operation and control of the substation and the power system generally, classified information should be available only to the limited group of users and must be protected from the unauthorized ones.

Substation database must perform several important tasks:

- store and organize the data collected and analyzed in the substation in a logical manner
- allow users for fast and efficient retrieval of data using customized queries based on multiple search criteria, such are types of events, time and location of measurement and event occurrence, specific IED type or ID etc.
- provide reports containing detailed information on events in the substation, such as fault types and locations, power quality disturbances, operations of protective relays, and operations and switching sequences of the circuit breakers
- Make the information available for the local/substation and system-wide use
- enforce referential integrity preventing the problems with the redundancy of data stored in the database
- requesting from the users additional information, not readily available from IED recordings or application reports
- support data validation by establishing data entry rules, verifying individual fields in database tables and using lookup tables

The format of data stored in the database depends on the IEDs providing the data, the applications performing the analysis, protocols used for data transfer and many other considerations.

The largest group of data in the substation are IED related data. In the substation database for Automated Analysis Substation System we organized them as follows:

- raw IED recordings. These are data collected in the field. There can be two types of these data: “logged” – recorded continuously during certain period of time, or “event” – the beginning of their recording is usually triggered by predefined conditions. Both “logged” and “event” data can be in different IED specific file formats.
- simulated IED recordings. They are generated by the AASS system and kept for the reference and comparison with the field measurements.
- verified IED recordings. These recordings contain corrected data, verified by the AASS application.
- IED configurations and settings contain IED device specific data, such as relay settings, DFR channel assignments etc.

The simulated and verified recordings are stored in the COMTRADE [2] or ASCII files and renamed according to the IEEE file naming convention [3] enabling more efficient retrieval and manipulation.

Apart from mentioned data, substation database contains the substation topology files, in substation configuration language (SCL). The language is defined as part of the IEC61850 standard enabling standardized way for describing the substation topology, communication interfaces and descriptions of available data [12]. Together with the topology files, related ATP substation models and the simulation templates are kept in the database.

Reports from the analysis and verification applications are stored into the database and organized in a way that enables their efficient retrieval for particular event of interest, based on the type, time and location of occurrence. Each application produces it’s own report containing different information, which could be redundant in some cases.

Last large group of data are application specific settings. Since the outcomes of analysis and verification application algorithms are dependent on values of various parameters empirically reached, keeping them stored in the database enables users to compare and establish the relationships between various settings and measurements data.

USER INTERFACE REQUIREMENTS

The user interface of the Automated Analysis Substation System can be divided into two parts. The first part is accessible from the concentrator PC and is called the Client Graphical User Interface (GUI), while the second one is available online, to the LAN/WAN users and is referenced as a Web application user interface.

The client GUI serves several important functions. One of the most significant is to display the real-time IED data to the users in the substation. The data can be either acquired from the field or simulated using the ATP program. The data can be in the form of samples of signal waveforms, mostly in COMTRADE file format, or stored in ACII textual files. The AASS features customized tool for viewing COMTRADE waveforms with capability to zoom in and zoom out the view of the waveforms with customized ratios. The tool enables for horizontal and vertical scrolling, panning, overlaying multiple waveforms in various colors etc.

In Figure 0 the screenshot of the client GUI is given, displaying the COMTRADE viewer tool and main topology window. In the main topology window of the client GUI, substation topology is graphically displayed. The layouts of the buses and feeders, equipment interconnections and statuses of circuit breakers and IEDs can be seen. Instantaneous values of branch currents node voltages can be observed at specific time instances such as fault occurrence, circuit breaker switching etc.

Finally, the centralized GUI integrates all the verification and analysis applications by providing single, easy to use interface. All the data collected from the substation are preprocessed and forwarded to the applications for more complex analysis. When the processing is done, the reports and verified data are displayed in the GUI, providing instantaneous feedback to the users.

One of the most important functional requirements of the centralized GUI is to enable seamless integration with the substation database. The GUI provides the forms and customized dialogs with options allowing the users to manually or automatically store the data into the database according to the established business rules.

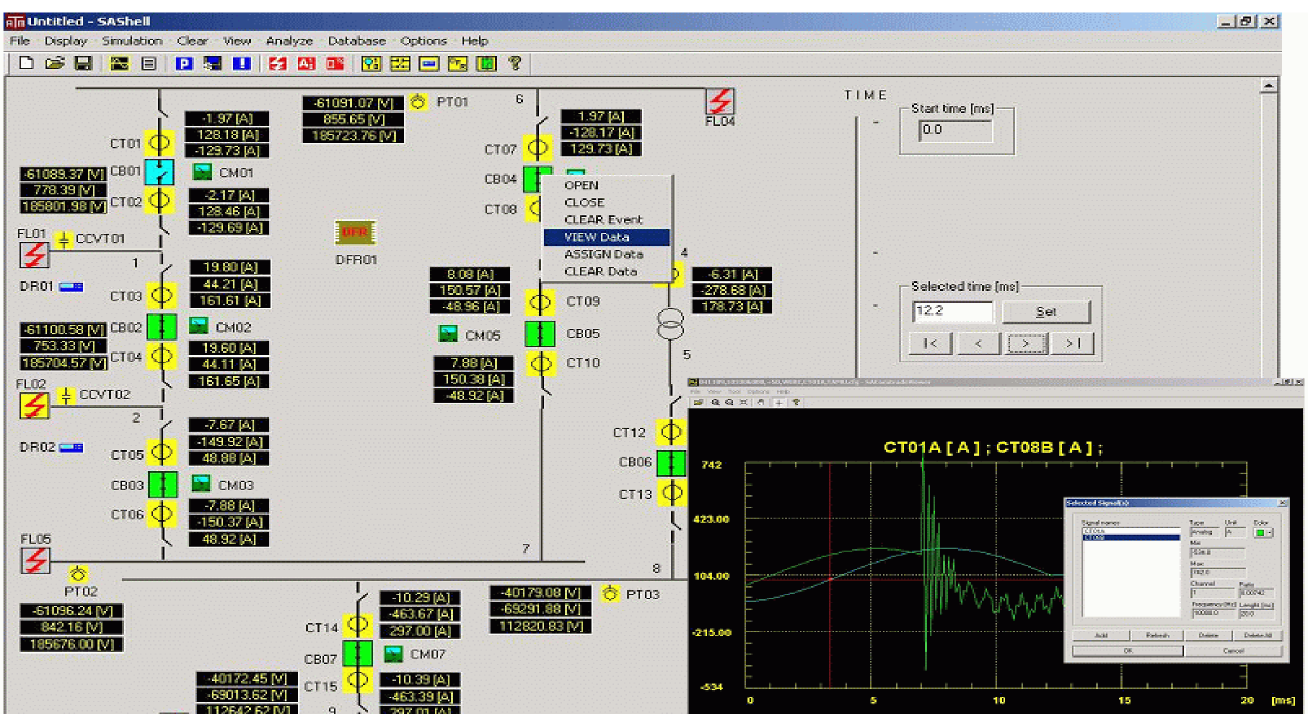

Figure 0 Screenshot of Centralized GUI

The client GUI provides support for data simulation. Using the toolbars and command menu, the simulation parameters such as length and frequency of the simulation can be set. There is an option to set the faults and enter some of their parameters such are location, type and resistance. Switching sequences of the circuit breakers can be set, as well as initial statuses of devices. Dialog for setting the faults and switching sequences is displayed in Figure 1. Customized dialog enables manual and automated assignment of measured and simulated data.

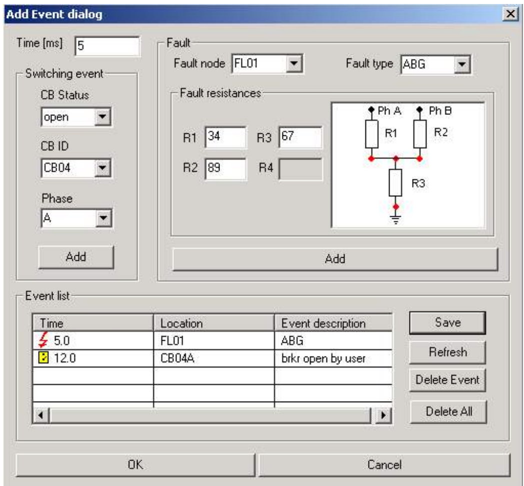

Figure 1 Dialog of Centralized GUI for setting the faults and switching sequences

The main requirements of the Web application interface in current implementation of the AASS is to enable online access to the substation data and reports stored in the substation database. Some of its functions are supporting the authorization and authentication of the users, advanced searches of the data based on multiple criteria, graphical displaying of the signal waveforms and analysis reports, remote classification of the reports and data based on levels of priority, file transfer between the substations and the control centers etc.

CONCLUSIONS

The paper presented the new Automated Analysis Substation System featuring eight functions for verification and analysis of substation data.

It uses a new approach for data verification based on two methods. By using the first method, correctness of the data is verified by comparing them with the redundant measurements available from the existing substation IEDs monitoring the same or similar parameters. The second method verifies the data by comparing them with the simulation results of appropriate substation model. This two verification methods are allowing for increased correctness and reliability of the data in existing substation systems, with no additional costs increase.

Analysis applications are extracting the information from the IED recordings such are fault types and locations, power quality disturbances, operations of protective relays, operations and switching sequences of circuit breakers. Relevant information are extracted, processed and presented to the users in the form of customized reports, enabling for faster and more comprehensive understanding of statuses and events in the substation and the overall system.

The CBMA and DPRA applications are not only monitoring the breaker and relay operation but are also analyzing the operating performances. Consequently, the functions they are performing are enhancing the equipment condition monitoring, providing for minimization of maintenance costs and extension of exploitation time.
Centralized archival of data implemented by the substation database allows for the historical analysis of collected data.

Finally, unified and centralized GUI and Web application enables easier access to the data by different groups of users of substation data and analysis reports.

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