DEVELOPING FUTURE SUBSTATION AUTOMATION STRATEGIES: SELECTING APPROPRIATE IEDs AND DEVELOPING NEW APPLICATIONS

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Abstract: The aim of this paper is to introduce two important issues when selecting new Intelligent Electronic Devices (IEDs) as a part of the substation automation system implementation, namely the evaluation means and new applications. For the evaluation purposes, several digital simulator applications are discussed together with the benefits obtained by utilizing the simulators. The evaluation of the IEDs prior to the purchase as well as in the field is described. Regarding implementation of new functions, the importance of the concept of data integration and information exchange is elaborated. It is pointed out that most of the new applications require unconventional use of data and information to yield specific benefits, which will justify the use of substation automation systems. The scope of the paper is restricted to discussion of various methodologies and generic tools and it is not aimed at discussing specific commercial products or services. In conclusion, the paper points out that the use of advanced IEDs and substation automation systems requires significantly different approach in evaluating and implementing the new solutions.

INTRODUCTION

Intelligent Electronic Devices (IEDs) is a generic name that covers various protection, control, metering and monitoring devices that are implemented using microprocessor-based technology. The devices may resemble the traditional solutions at the functional level such as individual meter or protective relay, but quite often the functionalities of IEDs are significantly enhanced so that they cannot be easily compared to a counterpart implemented using earlier technologies. As a consequence, evaluation of the performance of such solutions is not straightforward due to the complexity and performance improvements offered. As a result, new methodologies and tools are needed to perform the evaluation.

Besides the need to better understand functionalities of new IEDs and their performance characteristics, the designers of the future substation automation systems need to understand what are the new benefits that may be obtained by introducing non-traditional functionalities that are made possible through data integration and related processing at the substation level. The new functions may require different approach to database and user interface solutions and are expected to provide more automated means of handling the data and making related control decisions.

This paper addresses both issues: evaluation of IEDs and new functions. After a background section, which talks about the latest IED and substation automation standards and related business advantages, the paper concentrates on a discussion of digital simulators that may be used for evaluation of new IEDs. After that, a discussion of new applications aimed at automating the monitoring and control tasks is provided. The paper ends with conclusions and a list of references.

BACKGROUND

Two considerations are very important as the background: a.) Development of communication standards for data integration and information exchange and b.) Understanding the role of substation automation systems in the utility business. Each of the issues will be addressed separately.

Communication standards for substation and system automation

Over the last few years International Electrotechnical Commission initiated development of multiple standards for various automation applications found in system solutions such as Substation Automation System (IEC 61850), Energy Management System (IEC 61970 CIM extension), and Distribution Management System (IEC 61968) [1,2,3]. As a result, the complexity of system solutions has increased by enabling interconnection of various advanced IEDs at the substation level and processing the data coming from these IEDs at both the substation and control center level. Enabling the interchangeability of IEDs at the substation level opens new opportunities for utilities to select IEDs that fit their needs the best. In doing so the utilities do not have to worry if the selected equipment, if chosen from multiple vendors, is compatible since the new substation automation standard assures that new IED designs from all the participating vendors will be compatible. However, in selecting the equipment that best matches the needs, utilities have to make sure that their criteria and selection process are up to the task. If the purchase evaluations are done based only on the data provided in the vendor manuals, it might be rather difficult to decide what are the most relevant performance characteristics and to develop the ways to measure them. This leads to the need of having appropriate tools and methodologies for evaluating new IED designs. As an illustration, Table I outlines a few important performance characteristics and suggested performance measures for most common IEDs together with the means of evaluating the compliance with the performance criteria. It may be noted that the performance evaluation tool used in all cases is a digitals simulator capable of replaying both simulated and recorded waveforms [4].

Table I. IED Performance Characteristics and Means of Evaluation

IED Type	Performance Characteristics	Means of Evaluation
Digital Relays	Trip time; fault classification, selectivity; oscillography; fault location, operating character.	Simulating variety of faults to create transients; replaying phasors; generating status signals
Digital Fault Recorders	Frequency bandwidth, triggering mechanism, length of the recording memory; sampling rate, length of the pre-fault	Creating desirable waveforms through mathematical expressions; replaying both phasors and transients; generating status (contact)signals
Power Quality Meters	Classification and characterization capabilities in distinguishing PQ events; length of the recording memory; accuracy of measurement	Implementing reference PQ algorithms for performance comparison; replaying both precise reference waveforms and PQ disturbances
Circuit Breaker Monitor	Ability to analyze different breaker signals and make conclusions about breaker status	Generating trip and close signals as well as simulating other control circuit signals

Understanding the role of substation automation in the utility business

An obvious role is to implement all the substation devices as one integrated system so that the users and devices can exchange data and information. The role of providing users, other than the traditional protection and substation operation groups, with an opportunity to gain access to the data and information that can change their way of utilizing substation data is not so obvious. As much as the selection of IEDs is driven by the historical and traditional functions that a given utility may have implemented over the years covering its protection, monitoring and control needs, it should be understood that the selection of IEDs that constitute substation automation system may also be impacted by other more unconventional functions and needs that are yet to be recognized and formulated. The new competitive business environment forces utilities to formulate their strategies regarding productivity, quality and reliability of service, asset management, maintenance strategies, etc. One of the critical considerations for IED selection may be their role in supporting the mentioned functions, which in turn may mean that the IED evaluation should include the capability for their use in defining new applications. Table II illustrates some of the mentioned links between the IED properties, their impact on implementation of new functions, and expected benefits.

As a summary of the background, it appears obvious that selection of IEDs and understanding their properties has a far-reaching consequence. Implementing the best substation automation design and assuring that the system performance will significantly improve due to the ability to have multiple uses of the substation data is the main goal.

Table II. Role of IEDs in serving unconventional functions and users

IED Properties	Impacts on new functions	Expected benefits
Digital Relay: recording of circuit breaker (CB)currents	Can be used for monitoring circuit breaker duty cycle	Development of Better CB Maintenance strategies
Digital Fault Recorder: analyzing operation of relays, relay communication channels, and circuit breaker operations	Enables definition of new function for automated analysis of fault clearing sequences	Development of better protection schemes and applications; time savings in analyzing faults, relay and CB operations
Power Quality Meter: analyzing PQ disturbances	Enables definition of new function for automated detection, classification and characterization of PQ disturbances	Better understanding of PQ disturbances and their impacts on customers; time savings in analyzing disturbances
Circuit Breaker Monitor: analyzing of breaker operation and possible malfunctions	Provides ability to verify the system topology after each breaker operation	Knowing the topology enables more accurate state estimation and load flow calculations

SELECTING APPROPRIATE IEDs: DIGITAL SIMULATOR APPLICATIONS FOR IED TESTING AND EVALUATIONS

In performing evaluations of protective relaying IEDs, there are various scenarios:

- The need to evaluate IEDs before the purchase, which can be accomplished by using laboratory set-up of a digital simulator with an elaborate output power as well as modeling and simulation capabilities. In this case both field recorded as well as simulated waveforms can be replayed into a sample IED to assess the response and features of the IED under the specific transient conditions commonly encountered in the customer's system.
- The need to periodically test all the IEDs in various substations or troubleshoot miss-operation of an existing IED in any given substation, which can be performed in the field by using a portable version of the digital simulator. In this case the pre-defined test waveforms or waveforms that were captured during the disturbances that caused IED miss-operation can be replayed to the IEDs located in the substation to verify either the IED performance or better understand the miss-operation circumstances respectively.
- The need to have an easy and quick way of evaluating IED operation for fast restoration of critical transmission lines, which can be accomplished by having permanently installed digital simulators at the substations located at two ends of the line (s). In this case, performing end-to-end tests by applying data at both relaying systems at the two-transmission line ends simultaneously helps in carrying out the restoration procedures.

Laboratory Set-up of Digital Simulators

Laboratory set-up of digital simulator is widely used by IED vendors and their use is becoming more frequent in the utilities. The set-up consists of several software and hardware tools that have become widely available and affordable. Typical hardware comprises a simulator computer, communication subsystem, waveform reconstruction subsystem, voltage and current amplifiers, and digital I/O interface as shown in Figure 1.
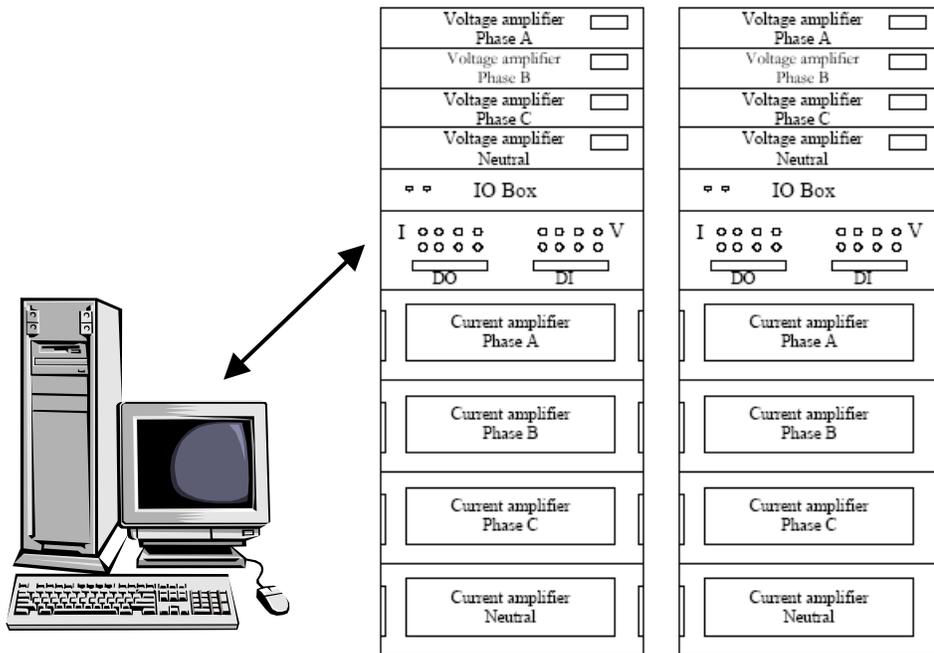

Figure 1. Two-terminal laboratory set-up

Digital simulator software has to possess a number of properties and functions to make the simulators indeed a useful tool in evaluating IEDs [5]:

- Ability to take field recordings from variety of other IEDs installed in substations so that the operation of new IEDs can be evaluated and compared to operation of others by subjecting it to the recorded waveforms and observing its reaction
- Suitability for modeling exact power system conditions and events in a given utility and testing IEDs under the circumstance closely resembling actual scenarios
- Capability of doing sensitivity studies through gradually changing input waveform characteristics to better understand IED behavior and performance under many diverse operating conditions
- Possibility for using experimental means to tune relay settings for complex applications allowing full benefit of various application options provided by different products
- Practicality of automatically performing thousands of tests for a large number of scenarios making the evaluation rather comprehensive while assuring a low cost

Portable Versions of Digital Simulators

The portable simulators are used for periodical routine maintenance tests of the substation protection IEDs, end-to-end tests during commissioning, trouble-shooting tests aimed at quick system restoration. This way the in-service IED performance can be evaluated and a judgment can be made regarding volume purchases for replacement of the old equipment with advanced IEDs such as the one selected for field evaluation. Since it takes significant time to take all the equipment to the substation, and to set up, wire, and calibrate the test system before the actual testing can be done, the process of setting up the equipment as well as using it has to be short and straightforward. An example of a portable simulator layout is shown in Figure 2. When considering the use of portable simulators, one should be aware of multiple options related to the benefits and disadvantages as shown in Table III.
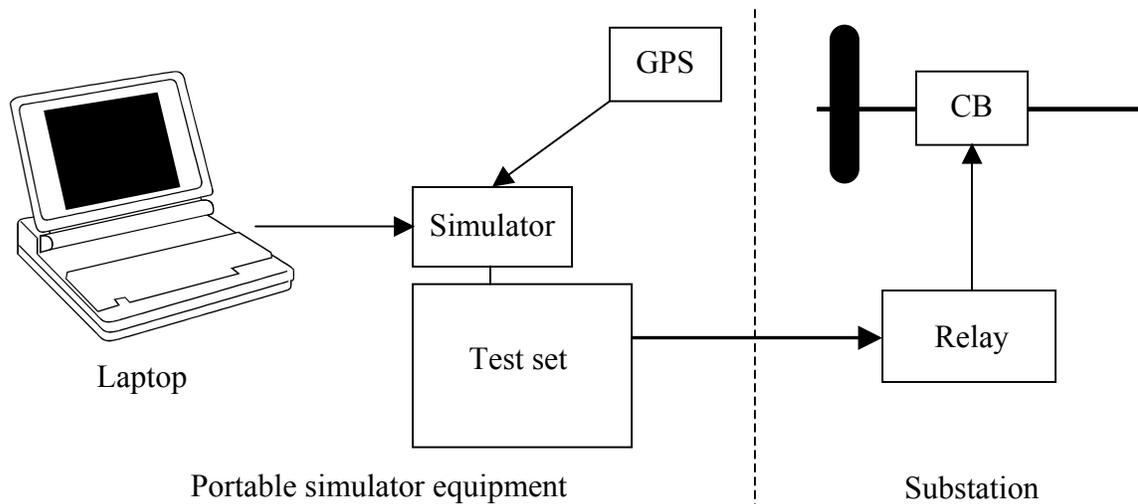

Figure 2. Portable simulator setup

Table III. Implementation options for the field simulator configurations

Implementation Option	Advantages	Disadvantages
Use simulator software with conventional tests set by using the test set interfacing language and hardware	No need to purchase power amplifiers and interfaces between PC and tests set	Performance of simulator software may be limited by performance of the tests set.
Use of simulator software with conventional test sets by interfacing the PC D/A output board to the tests set amplifier analog input	Full performance of the simulator software and speed of the waveform replay can be enhanced	Additional cost for PC D/A output card has to be added to the cost of the software, which is a low cost item
Use of simulator software and specialized D/A output board together with custom power amplifiers	Full performance combined with full flexibility to package and configure the tests set hardware	The additional cost includes PC D/A output card as well as the non-trivial cost of power amplifiers

Digital Simulators Permanently Installed In Automated Substations

One possible new approach to application of digital simulators being permanently installed inside substations is shown in Figure 3. Digital simulator equipment with a capability to replay signal waveforms synchronized by GPS is permanently installed in each substation. When regular testing or troubleshooting is needed, the measurements typically coming from CTs and VTs are simulated and applied as simulator outputs through the multiplexer (Mux) to IED inputs (Relay in Figure 3.). Use of the simulator equipment with GPS receiver for synchronized replays of simulated wavforms enables end-to-end testing of both the installed equipment (e.g. protection relays) and communication channels.
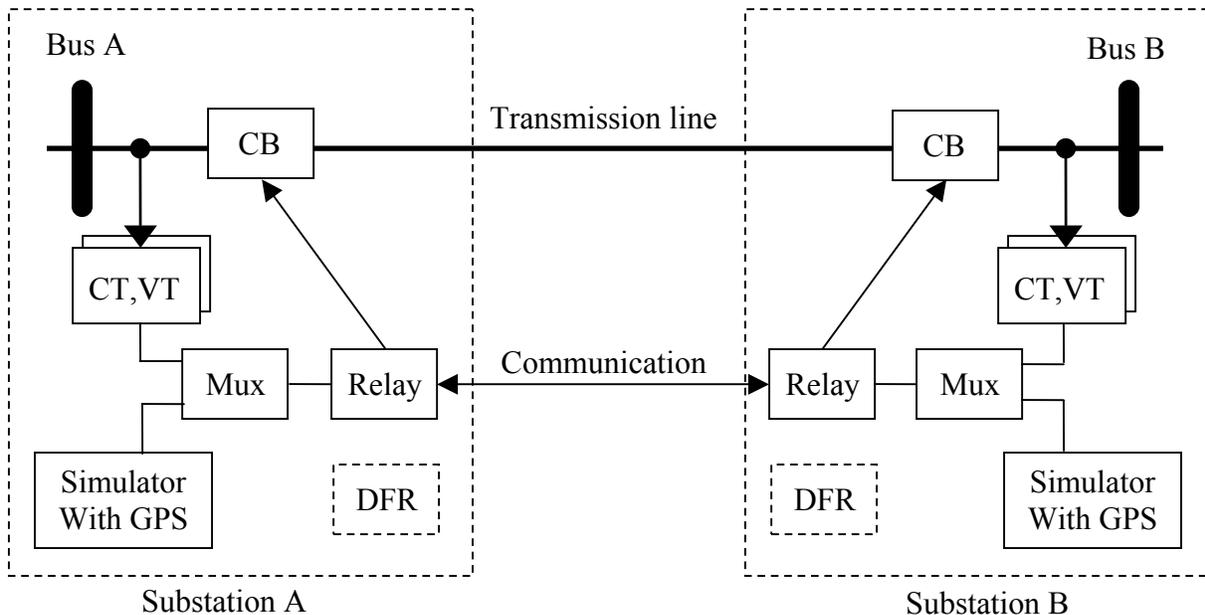

Figure 3. Digital simulator permanently installed in substations

Having digital simulators permanently installed inside the substations will dramatically reduced the time needed to set up the test environment for both regular testing and troubleshooting sessions. Furthermore, utilizing the communication both inside the substation and between substations and protection engineer's offices enables performing the end-to-end testing remotely. Test waveforms based on either recorded or simulated events/faults can be downloaded to simulators in each substation remotely, and then the replaying of the waveforms can be synchronized using GPS controlled triggering.
In addition to protective relays, any other IEDs as well as their application can be tested and evaluated with the same approach. Having in mind that substation automation may accommodate several newly developed applications, permanently installed simulators can be used for evaluating, verifying, and fine tuning of new applications through a remote access to permanently installed simulators.

DEVELOPING NEW APPLICATIONS: USE OF ADVANCED SUBSTATION IEDs FOR LOCAL AND EMS MONITORING APPLICATIONS

While designing substation automation systems, several important issues need to be considered when selecting IEDs that will be included in the solution:

- The substation automation system will have an abundance of redundant data collected by IEDs connected to the same switchyard. Can this redundancy be utilized to improve consistency and accuracy of substation database?
- The substation automation system will introduce an additional processing power at the substation level. Can this processing power be utilized to perform pre-processing for some EMS functions, which will make them more robust and accurate?
- The substation automation system will collect large amount of data related to the given events and/or equipment operation. Can this data be automatically processed to reduce the time and inconsistency of data analysis in comparison with the situation where different operators are doing this analysis manually?
- The substation automation system will provide integration of data coming from different IEDs but related to the same events and/or equipment operations. Can this variety of data from different IEDs be utilized to perform better overall analysis of the given events and/or equipment operations?

To better monitor power system equipment and disturbances, data coming from the following IEDs is considered (Figure 4): digital fault recorders (DFRs), digital protective relays (DPRs), power quality meters (PQMs), remote terminal units (RTUs), sequence of event recorders (SERs), programmable logic controllers (PLCs), circuit breaker monitors (CBMs), operator meters (OPMs).
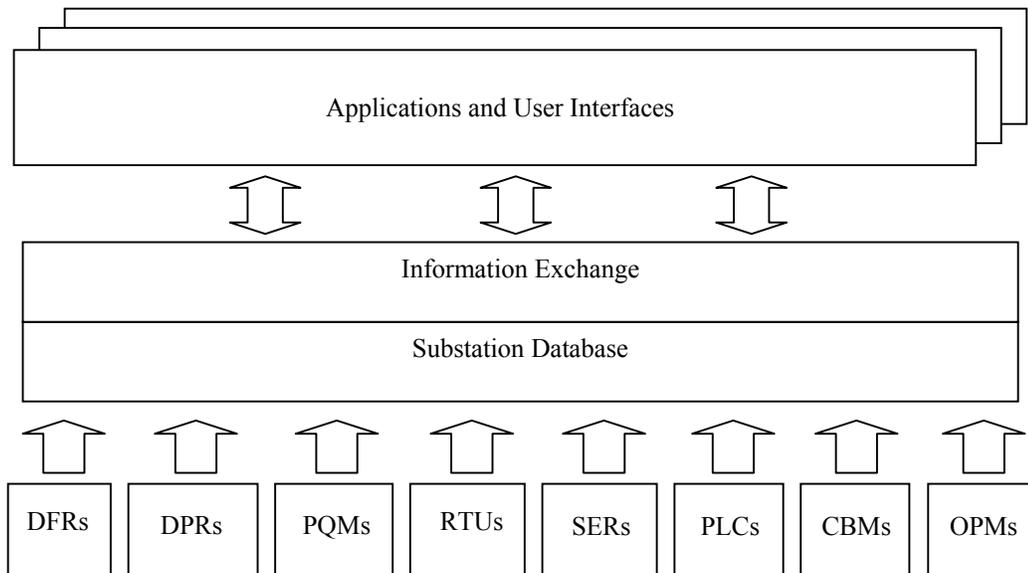

Figure 4. Data sources in a substation automation system

Use of IED data for substation tracking functions

The substation tracking system enables verification of the data being collected in the substation and ensures the database consistency. The following three applications can illustrate how IED data may be used for this purpose:

- Verification of Substation Database (VSDB)
- Two-stage State Estimator (TSSE)
- Substation Switching Sequence Verification (SSSV)

Verification in substation database (VSDB) performs collecting, processing and data consistency checking at the substation level. This application consists of several steps [6]:

- Analog and digital measurements are collected around substation
- All other data gathered from IEDs should be added to this set of measurements as well.
- All acquired measurements are combined and processing and consistency checking is performed.
- Redundant data is eliminated and redundancy is used to create an improved set of measurements.
- All detected measurement errors are filtered out. Output data are more concise, reliable and consistent.
- There are six processing and consistency check algorithms, some are handling analog measurements (redundant branch current measurements algorithm and Kirchhoff's Current Law algorithm) while others are handling topology measurements (branch status determination algorithm and branch current and status consistency algorithm).
- There are two more algorithms that examine changes in analog and digital measurements throughout the time (from snapshot to snapshot) and report transitions in the transmission line and load connectivity.

Two-Stage State Estimation (TSSE) function detects/identifies the topology errors. This algorithm normally includes three parts [7]:

- First Stage State Estimator. The first stage state estimation is nothing but a conventional one, which is based on the bus/branch model. Most of the conventional state estimation methods capable of bad data processing are used directly. Here we use Weighted Least Absolute Values (WLAV) method due to its ability to exclude bad data.

- Suspect Substations Identification. After the first stage state estimation, we need to detect and identify any existing topology errors. Normally, this detection/identification procedure is based on the normalized residual analysis.

- Second Stage State Estimation and Correction of Topology Errors. The detailed models of suspect substations are incorporated into the bus/branch model at this

stage. The generalized state estimation, which can consider zero-impedance branch runs based on this expanded model.

Substation Switching Sequences Verification (SSSV) is used to verifiy if all the switching sequences are performed correctly. It consists of the following processing steps [8]:

- Determination of optimal switching sequence for each type of fault condition or load transfer operation.
- Analysis of the measured switching sequences.
- Comparison whether the measured switching sequence is the optimal one.
- This function uses data from several IED specific applications such as DFRA, CBMA and DPRA.

Use of substation data for automated analysis of faults and disturbances

Automated analysis functions can be identified as device-specific applications that provide automated analysis of data collected by selected IEDs in substation such as DFRs, CBMs, PQMs and DPRs. Other functions may be identified as substation-wide or even system-wide analysis applications. As an example, four device-specific and one system-wide automated data analysis applications are briefly discussed next:

- Digital Fault Recorder Data Analysis (DFRA)
- Circuit Breaker Monitor Data Analysis (CBMA)
- Power Quality Monitor Data Analysis (PQMA)
- Digital Protection Relay Data Analysis (DPRA)
- Fault Analysis Including Fault Location (FAFL)

Digital fault Recorder (DFR) data analysis (DFRA) is an application that conducts automated analysis of fault records captured by digital fault recorders (DFRs) and disseminates event reports. Event analysis has following goals [9]:

- Detection and classification of faults and disturbances
- Verification of the correctness of the protection system operation
- Verification of circuit breaker operation
- Calculation of fault location

Circuit breaker monitor data analysis (CBMA) evaluates performance of the circuit breaker based on the analysis of data taken from the control circuitry. The following are main properties [10]:

- It requires input data in COMTRADE file format, with predefined signal names and order [11].
- At the end of processing, it gives the 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.

Power quality meter data analysis (PQMA) is a powerful application which can be used for power quality analysis and modeling. It integrates following functions [12]:

- Converting, retrieving and managing PQ meter files
- Modeling of power quality events
- Online replaying of recorded events or created signals
- Implementing event detection and classification
- Enabling waveform characterization
- Providing data file compression

Digital protective relay data analysis (DPRA) has several applications such as:

- Consistency checking of the data of various relay files. Checking is performed by comparison among osillography file, fault report and event report.
- Verification of correctness of the data obtained from various relay files. Comparing the reference data in the osillography file and fault report performs verification
- Providing results to some higher-level applications, such as Fault analysis including fault location (FAFL), described next.

Fault analysis including fault location (FAFL) includes the following [13]:

- It uses 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.
- Analysis is partially based on processing results obtained from device specific applications. Other applications, such as DFRA and CBMA provide information for enhanced fault analysis.
- It performs local as well as system wide analysis of the faults.

CONCLUSIONS

As a result of the discussion presented in the paper, the following defining elements of the substation automation strategy can be outlined:

- New IEDs are complex and have variety of settings and functions. To be able to utilize them, one needs to very well understand their application features and performance properties. The use of different digital simulators can help in the process of testing and evaluating the IEDs and making more informed decisions
- Selecting new IEDs and integrating them in one substation automation system can offer variety of benefits. To make sure the benefits are fully explored, one needs to think of new functions that can add the value to substation automation solutions
- Present practices regarding IED evaluation and new function specification are very limited and need to be changed to accommodate new business needs in the industry. The new IEDs need to be selected to enhance reliability and security of power system operation as well as operator productivity and decision making

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