Intelligent Processing of IED data for Protection Engineers in the Smart Grid

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***Abstract*—In the Smart Grid, protection engineers should be provided with advanced tools to execute event analysis more effectively making sure the system is restored as quickly as possible. Since the manual event analysis is a time consuming process, this paper proposes a scheme for real-time automated collecting, analyzing, archiving, and displaying of Substation Intelligent Electronic Device (IED) data generated during a power system events. How the relevant information is extracted to generate a customized report, especially considering protection engineers' needs is discussed. Several intelligent IED data analysis application tools are incorporated for the purpose of effective IED data processing. A software application named "Report Generator" is developed for the purpose of data integration and information exchange to create the report with a predefined format. A simulation case is given for more detailed description of the automation process. This solution ensures high efficiency in root-course analysis aimed at understanding and trouble-shooting relay operations, resulting in improved reliability of power system operation.**

I. Introduction

In the Smart Grid, Substation Automation System (SAS) performs an important role in economic power system operation and stability control, aiming at assuring continuous and reliable power supply [1]. Due to the latest development in other disciplines such as computer engineering, communication network and signal processing , a lot of new devices and techniques are developed for the purpose of more effective operation, event handling, asset management, as well as maintenance planning [2,3]. Development of Intelligent Electronic Devices (IED) serves as a typical example [4]. Generally speaking, IED is a designation which describes various microprocessor-based protection, control, metering and monitoring devices. Compared with traditional solutions at the functional level such as individual meter or protective relay, IED functions are much more enhanced. For example: (1) modern Digital Fault Recorders (DFRs) are used to capture data from various events with a high sampling frequency and at the same time may be used to host automated event analysis function [5]; (2) modern Digital Protective Relays (DPRs), not only can perform traditional functions of a protective relay, but also have the capability to carry out data recording, fault location, event analysis, etc [6]; (3) Circuit Breaker Monitors (CBMs) are emerging devices specially developed for the monitoring of modern circuit breakers, but also equipped with oscillography and data analysis capability [7].

As more and more multi-function IEDs are being installed into the power system, there will be massive volumes of data coming from diverse points of IED installation even for the same event. The protection engineers are concerned with the event type, event location, performance of protective relays, operation of related fault clearing equipments (Circuit Breakers, auto-reclosing relays, etc). The issue is how to use data from various IEDs such as DFRs, DPRs and CBMs to extract the most useful information to carry out event analysis more efficiently, and at the same time provide some conclusions about the remedial measures or actions that need to be taken immediately (fault repair, and equipment restoration) [8, 9]. To perform such task, automated integration of data and exchange of corresponding information provided by different types of IEDs is used.

An automated data integration and information exchange is not very easy to implement considering the existing proprietary analysis software packages that use their own standards, protocols, formats, etc, which are typically provided by different device vendors [4].

Due to the fact that this event analysis problem is complex resulted from involvement of humans in the decision making, artificial intelligence techniques have been widely used in this area. Significant research has been carried out for the fault and protection system analysis so far: expert system and reasoning modeling to analyze protection system, was used in [10]. A real time tool for monitor relay operations for transmission lines was proposed in [11], rough classification method to extract substation event information, etc, was used in [12], and rough set theory in diagnosis for intelligent field devices was applied in [13].

Most of the proposals focused on the operation diagnosis at the device level. This paper proposes a systematic solution for automated IED data processing at the system level. Special attention is given to protection engineers' unique needs and it focuses on describing how the relevant information is extracted to generate a customized report for protection engineers. This way, the protection engineers can obtain more accurate event details, get more comprehensive understanding of the relay operations, including the

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performance of fault-clearing equipment, and accordingly take more effective remedial measures in a timely manner.

The paper first gives a background of the types of IEDs used, and then proceeds with descriptions of the data integration and analysis parts. An implementation example is given next. Some conclusion and references are given at the end.

II. BACKGROUND

Three types of IEDs considered in this paper as an example of possible IED types used in substations are DPR, CBM and DFR.

A. Digital Protective Relay (DPR)

Two DPRs used in the example demonstration utilize vendor specific software for data extraction. Customized event report and recorded data files are generated and made available, respectively as shown in Table I.

B. Circuit Breaker Monitor (CBM)

Records presented in this paper are obtained by a circuit breaker response recorders used to emulate CBMs, monitoring the operating condition of the control circuit of two circuit breakers. The corresponding recorded data for an event is listed in Table I.

C. Digital Fault Recorder (DFR)

The Digital Fault Recorder (DFR) used in this example records event data in COMTRADE 99 standard format as shown in table I. There are 16 analog inputs for voltage and current waveform recording, and 8 digital inputs for digital (contact) signal monitoring, such as trip signals issued by two DPR and circuit breaker status.

III. AUTOMATED INTEGRATION OF IED DATA

Automated Event Analysis (AEA) software package developed in earlier projects is used here to perform automated data processing for fault events [14]. The AEA application works with following groups of data according to Table I:

TABLE I. IED DATA SUMMARY

IED	File Type	File Format
DPR1	Oscillography File	COMTRADE 99
	Event Report	Custom SEL Event Report Format
DPR2	Oscillography File	COMTRADE 99
	Event Record	Custom GE Event Report Format
	Fault Report	Custom GE Fault Report Format
CBM	Waveform File	COMTRADE 99
DFR	Waveform File	COMTRADE 99

- Event data (ASCII and binary COMTRADE, ASCII text)
- Log data (ASCII and binary COMTRADE, ASCII text)
- Analysis Reports (ASCII text)

There are five key implementation issues as follows:

A. Nomenclature Mapping

The nomenclature that includes definitions of power system components, their locations in the power system, and related power system model designations have not been fully standardized across different utilities and IED vendors. As the first step, the nomenclature mapping for the three types of IEDs mentioned in this paper is accomplished by defining a mutually interpretable reference.

B. IED configuration

The configuration of different types of IEDs requires management of corresponding settings using the AEA software Graphic User Interface (GUI). For each IED, the responsible staff will manually enter the information about existing IEDs, designation, vendor, model and related local folders into the program. The program will save the information into a standard XML format file. After that the recording, acquisition and conversion of IED data needs to be configured to meet the following needs:

- Log data needs to be uploaded from IEDs by using vendor software and stored into the predefined folders on substation PC.
- Event data needs to be automatically sent by IEDs after the recording is triggered. The data is stored to the predefined folders on substation PC shortly after event occurrence.
- IEDs need to be synchronized with GPS time signal provided either from Substation PC or from internal GPS receiver.
- Other settings (IED parameters, monitoring frequency, folders, and communication with the PC) should also be configured.

C. DATA format

The IEEE COMTRADE 1999 standard file format aiming at the information interchange between different IED types or IEDs from different vendors is used in this application [15-17]. This standard defines common format for exchange of data files related to various types of fault, tests, or simulation data for electrical power systems. Issues of sampling rates, filters, and sample rate conversions for transient data being exchanged are also provided.

D. File naming convention

Standardized IEEE file naming convention for the time sequence data (C37.232-2007) [18] is used for more efficient and simple file management. The file naming solution, which contains unique information about an event (date, time, station, company, duration, location etc), can enable easier handling of large volume of files by allowing unique file identification.

The file extension will depend on the file type and the file name will consist of mandatory and optional fields according to the IEEE file naming convention standard developed by the Power System Relaying Committee. All fields are delimited by comma separator. For all groups of data, mandatory fields will follow the format from Table II:

E. Automated DATA analysis

Three intelligent analysis application software packages are incorporated, (together shown as Intelligent Analysis Application as shown in Fig. 1):

1) Digital Fault Recorder Analysis (DFRA)

The Digital Fault Recorder Analysis (DFRA) [19, 20] application provides automated analysis and integration of DFR event records. It provides import filters for different DFR native file formats and their conversion to COMTRADE format. Once converted to COMTRADE file format, all the event files are being analyzed utilizing signal processing and rule-based expert system. The outcome of DFRA is a conclusion report – (represented by DFRA.txt).

2) Digital Protective Relay Data Analysis (DPRA)

The Digital Protective Relay Data Analysis (DPRA) application performs an expert system based analysis, which automates validation and diagnosis of relay operations. It takes relay event reports and setting files as inputs, displays their contents using graphical user interface, and utilizes embedded expert system to automate the analysis and generate a concise report.

Validation and diagnosis of relay operation is based on comparison of expected and actual relay trip status and timing of logic operands. If expected and actual status and timing of an operand are consistent, the correctness of the operand is validated. If not, failure or mis-operation is identified and diagnosis is initiated to trace the reasons by the logic of the cause-effect chain.

The outcome of DPRA is a conclusion report especially for relays– (represented by DPRA.txt in Fig. 1) [21].

3) Circuit Breaker Monitor Analysis (CBMA)

The Circuit Breaker Monitor Analysis (CBMA) application performs analysis of records of waveforms taken from the circuit breaker control circuit using a Circuit Breaker Monitor (CBM) device. Monitored signals include “Trip or Close Initiates”, “A or B Contacts”, “Trip or Close Coil Currents”, “X or Y Coils”, “Phase Currently”, and “DC voltages” through out the circuit breaker open/close operations. The solution is implemented using advanced wavelet transforms for waveform feature definition, feature extraction and an expert system for temporal reasoning and decision making.

TABLE II. FILE NAMING CONVENTION

File name	Yyyy mmdd	hhmm ssmm m	Xyz	ssss	dddd	cccc
length	Fixed length (8)	Fixed length (9)	Fixed length (3 or 2) (-5D, -5A, -5S, UT)	Variable length	Variable length	Variable length
Mean-ing	Start date	Start time	Time code	Station identifier	Device identifier	Company name

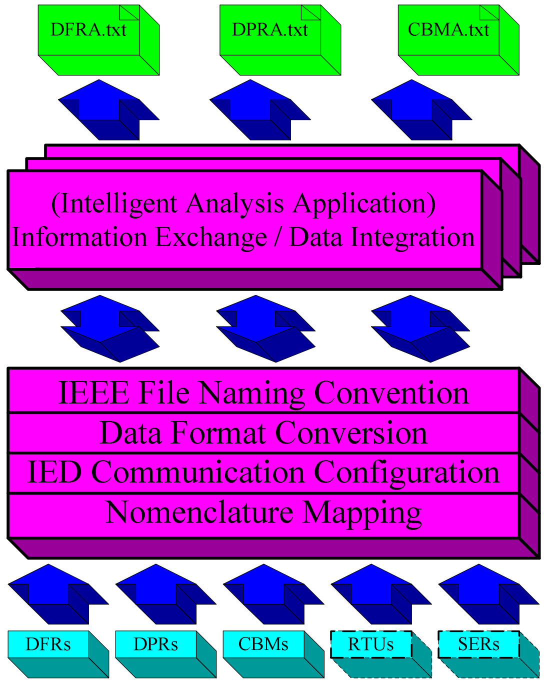


Figure 1. Automated integration and analysis of IED data

TABLE III. OUTPUT FILES OF AEA SOFTWARE APPLICATION

Applications	**File Type**	**File Format**
CBMA	CBM Device Recordings	Binary COMTRADE 99
	Analysis Report	ASCII TEXT
DPRA	Relay Event File	ASCII TEXT
	Waveform File	Binary COMTRADE 99
	Relay Fault File	ASCII TEXT
	Analysis Report	ASCII TEXT
DFRA	Waveform File	Binary COMTRADE 99 (w/o HDR file), Rochester File Format
	Analysis Report	ASCII TEXT

The outcome of CBMA is also a summary report containing operation details and conclusions for circuit breakers, as shown in Table III with other report files – (represented by CBMA.txt in Fig. 1) [22].

IV. Generation of Event Reports for Protection Engineers

Utilizing the three software packages mentioned earlier, the most important information from three kinds of IEDs is extracted. This information includes details of IED operation with regard to the same event, as discussed in section III.

The software package discussed here is called “Report Generator” for Protection Engineer. It is developed specifically for protection engineers. As shown in Fig. 2, its function is to take the three kinds of analysis report files

(DFRA.txt, DPRA.txt, CBMA.txt) as input, and to create a customized report for protection engineers– (PRENG.txt) at the occurrence of each disturbance or fault event. Each generated report consists of four parts, namely "Event Detail", "Relay Information", "Circuit Breaker Information", and "Suggested Actions". In Fig.2 the generated report is shown as the dotted box with four green blocks included, each of which stands for one part of the report.

A. *Event Details*

There are two sections in this part of the report. First section gives some general information about the event type, time of event, substation name, as well as affected circuit name. If the event is a fault, the second part will provide more detailed information about the fault type (for example, single phase A to ground fault), fault location, including the fault inception time and clearance time using "cycles" unit. One key point is that the fault detail information has been validated and integrated between DFRA.txt and DPRA.txt reports, so the accuracy and comprehensiveness of the information provided is enhanced here. In the cases where the information in these two reports does not match each other, the software generates a warning notice and the specific mismatch will be shown.

B. *Relay Information*

This part also has two sections. In the first section, the profiles of relays including the device name and ID are given. In the second section, the goal is to provide a concise conclusion about the correctness of operation for each protective relay. The conclusions are expressed as "Normal" or "Abnormal". The "Normal" means the actual operation of signals or operands for the relay is as expected. The "Abnormal" means the actual operation of signals or operands is different from expected: delayed, or mis-operated, or the recorded operations in the DFRA.txt file and DPRA.txt file do not match each other.

C. *Circuit Breaker Information*

The first section in this part provides the profile data of related circuit breaker. The content and conclusion in the second section comes from DFPA.txt and CBMA.txt files after data validation and integration. It tells protection engineers whether or not the operation of circuit breakers is correct. The predefined term "Normal" and "Abnormal" are again used here, with similar definitions as mentioned above: "Normal" means the actual opening or closing operation, or the control circuit signal behavior is correct, and "Abnormal" means the opposite, or the circuit breaker operation information (for example, opening or closing) in DFRA.txt and CAMA.txt do not match each other.

D. *Suggested Actions*

Based on conclusions obtained from the three reports, an intelligent analysis is performed to provide some concise suggested actions which should be taken by protection engineers immediately if possible. These suggestions for example can give guidelines for protection engineers to check the setting of certain protection elements of a specified protective relay. If some of the reports (DFPA.txt, DPRA.txt, CBMA.txt) which serve as input to the software need to be further investigated by protection engineer personally due to very complex event circumstances, they are listed and shown with direct link provided in this part.

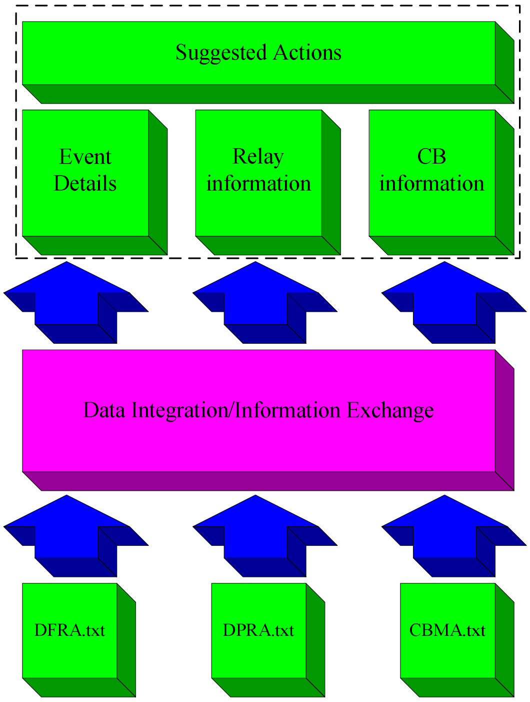


Figure 2. Report Generator for Protection Engineers

V. EXAMPLE

Taking advantage of a laboratory test setup, shown in Fig.3 [23], a substation protection scenario – with breaker and half bus configuration (Selected substation from CNP) was built to evaluate our solution. In this case a transmission line is protected by two circuit breakers - middle breaker and bus breaker, and they are tripped by two (redundant) digital protective relays from different vendors, as shown in the upper part of Fig. 4. DFR and CBM are also used for event capturing and circuit breaker monitoring,

In this simulated system, the power system transmission line model is first constructed using ATP/ ATPDraw software package [24] as shown in the lower part of Fig.4, and then BGEN and Relay Assistant commercial packages are used to generate desired fault scenarios and save related measurement files in a specified repository [25]. The files are used by the simulator in the next step to generate physical status signals , as well as analog voltage and current signals, which serve as input for two CBMs, one DFR and two DPRs as mentioned above. The hardware structure of this simulation system is shown in Fig. 5.

Figure 3. Lab setup for substation protection scenario

During a simulated event, the disturbance data and related information are recorded by each IED, and then the automatic processing of these records is done using the AEA software with the three intelligent analysis tools integrated. After that the output analysis report is automatically sent to the "Report Generator" for Protection Engineers and a customized report with predefined formats is created.

Here a sample generated report is provided for a detailed case of relay-fail-to-trip type of event which occurred during a transmission line single phase to ground fault.

The event description is shown in Table IV and the generated sample report for protection engineers is shown in Fig. 6.

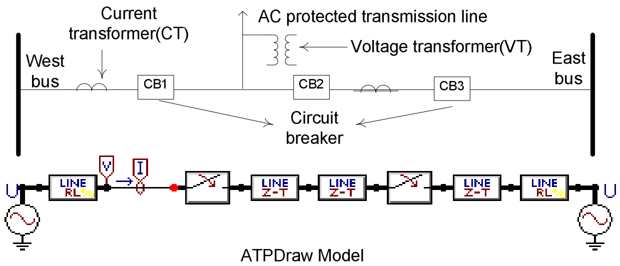


Figure 4. Power system model for simulation

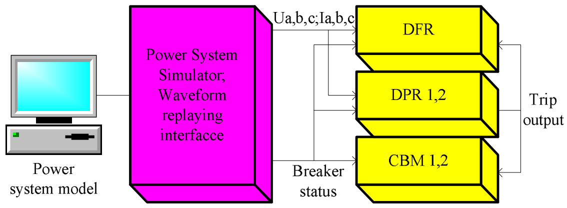
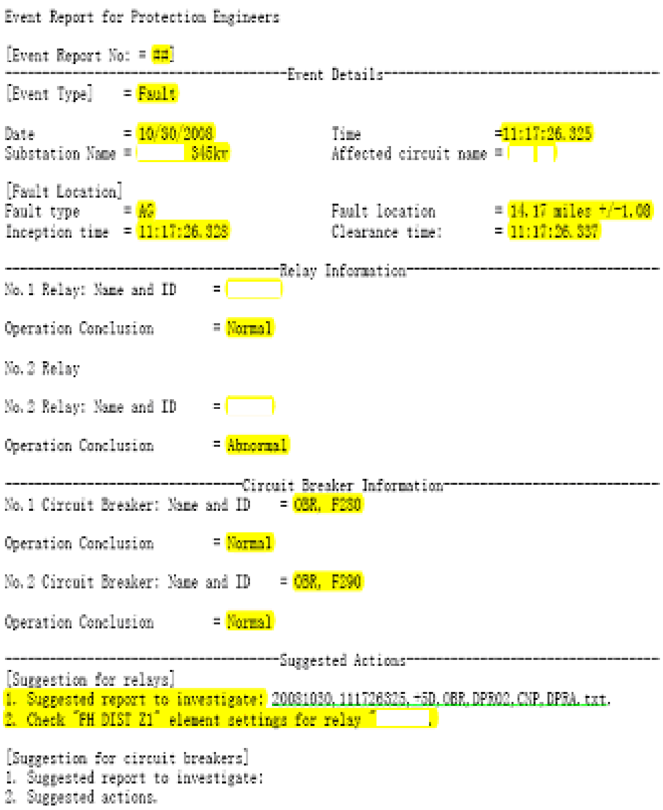


Figure 5. Simulation system structure


Event Report for Protection Engineers

[Event Report No: = ##]

--Event Details--

[Event Type] = Fault

Date = 10/30/2008 Time =11:17:26.325

Substation Name = 345kv Affected circuit name =

[Fault Location]

Fault type = AG Fault location = 14.17 miles +/-1.08

Inception time = 11:17:26.328 Clearance time: = 11:17:26.337

--Relay Information--

No.1 Relay: Name and ID =

Operation Conclusion = Normal

No.2 Relay

No.2 Relay: Name and ID =

Operation Conclusion = Abnormal

--Circuit Breaker Information--

No.1 Circuit Breaker: Name and ID = OBR, F230

Operation Conclusion = Normal

No.2 Circuit Breaker: Name and ID = OBR, F290

Operation Conclusion = Normal

--Suggested Actions--

[Suggestion for relays]

1. Suggested report to investigate: 20081030,111726325,-5D,OBR,DPR02,CNP,DPRA.txt.
2. Check "PH DIST Z1" element settings for relay " ".

[Suggestion for circuit breakers]

1. Suggested report to investigate:
2. Suggested actions.

Figure 6. Sample Report for Protection Engineers

TABLE IV. EVENT DESCRIPTION

Fault Type	**Fault Location**	**Protection zone**	**IED/Device failure**
AG	40% (12.6 miles)	Z1	Back up fails to trip

VI. CONCLUSIONS

The described solution in this study is aimed at automated processing of substation IED recorded data and generating information-rich and format-efficient report describing IED operation for protection engineers. This smart solution ensures high efficiency in root-course analysis for understanding and trouble-shooting relay operations, resulting in improved protection and reliability of the Smart Grid.

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