NEW APPROACHES TO EXPERT SYSTEM UTILIZATION FOR FAULT DIAGNOSIS

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Abstract– Automated fault analysis is of interest to both operators and protection engineers for different reasons. Operators need to confirm faulted sections before a restoration is attempted. Protection engineers need to analyze operation of relays, breakers and communication equipment in order to identify misoperations. New approaches using expert system and signal processing techniques for fault analysis are presented in this paper. The source of data are digital fault recorder (DFR) files. A solution has been tested using field data and the preliminary results confirm benefits of such an approach.

Keywords: Expert System, Signal Processing, Fault Analysis, Digital Fault Recorders

INTRODUCTION

The problem of fault analysis occurs when protection engineers, maintenance crews, substation operators or dispatchers need to know the power system operational state shortly after occurrence of a fault. The various groups of utility personnel have their own reasons for the analysis since their actions may have specific objectives and consequences. Typically, these groups also use different equipment to collect data needed for the diagnosis [1].

The most common approach to fault analysis is implemented today using Supervisory Control and Data Acquisition (SCADA) systems. In this case, the operators are concerned with switching state of the power system after the protection relays have operated [2]. This approach assumes that SCADA data base is utilized as a source of data for fault analysis. An expert system implementation of the software that will automate fault analysis is usually based on use of the contact data coming from circuit breakers, switches and protection relays. This approach has some inherent limitations due to the fact that temporal relation between various contact states is not preserved within the SCADA data base. Other difficulties are caused by potential SCADA communication errors which may alternate the contact states. All of this makes an efficient and extensive analysis of faults based on the SCADA data base very difficult to implement [3].

This paper discusses new approaches to fault diagnosis that are still based on utilization of expert systems but the source of data is different. These approaches rely on both contact data and analog waveforms as sources of information. This data can easily be captured by digital fault recorders, digital protection relays or integrated digital control and protection systems [1].

The new approaches have the main advantage of using data that is redundant and has a temporal element inherently available. The analog waveforms provide redundant information about contact status since each contact change may directly be associated with a change in the waveforms. The analog waveforms also provide a unique time reference for all events.

The first part of the paper is devoted to a detailed description of the fault analysis problem. Various implementation approaches are presented next. As an example of a new approach, an expert system developed by Texas A&M University under sponsorship of Houston Lighting & Power Company is discussed [4-6]. Future directions in fault analysis implementation and conclusions are outlined at the end.

PROBLEM DESCRIPTION

Fault analysis is an issue that may mean different things to various groups of personnel within a utility company. Table I summarizes some of the most common terms used to describe various fault analysis functions and their implementations. This paper uses the fault analysis to designate fault detection, classification and location, as well as diagnosis of operation of circuit breakers, relays and communication equipment.

Another important aspect of fault analysis is equipment used to obtain relevant data. A number of different sources of data exist in a substation and their data characteristics are most relevant in selecting a given solution [1]. Figure 1 gives an overview of the most common sources of data available in a substation. This paper discusses possible solutions using digital fault recorders (DFRs) as a source of data.

Finally, it is important to recognize events of interest for the fault analysis. The following are examples of these events:

- Fault clearance at the monitored substation.
- Fault clearance at some other substation.
- Self clearance.
- No clearance of a fault.
- Reclosure failure.
- Reclosure success.
- "No fault" disturbance.

IMPLEMENTATION APPROACHES

As mentioned earlier, there are two broad categories of implementation approaches. One is related to the use of contacts as the source of data while the other one assumes that both contacts and analog signals are utilized. The first category has been extensively explored in the past and a number of solutions were proposed and implemented [3]. It has been demonstrated that this category enables analysis of the

Table I. Summary of Fault Analysis Approaches

Equipment	Data	Function
Seq. of Events (SOE) Recorders	Indications, Alarms	Event Analysis
RTU/SCADA	Indications, Alarms Scan of Analogs	Alarm Processing Fault Diagnosis
Digital Fault Recorders (DFRs)	Samples of Contacts and Waveforms	Fault Detection, Classification and Event Anal.
Fault Locators	Samples of Analog Wavefomrs	Fault Location
Fault Detection, Classification and Location	Recording with Synchronized Sampling	Synchronized Samples of Analog Wavefor.

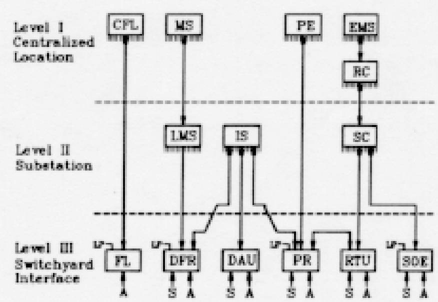

Figure 1. Equipment for Fault Analysis

CFL – Centralized Fault Location
MS – DFR Master Station
PE – Protection Engineer's Console
EMS – Energy Management System
RC – Regional Control Center
SC – Substation Computer
IS – Integrated Substation System
LMS – Local DFR Master Station
FL – Fault Locator
DFR – Digital Fault Recorder
DAU – Data Acquisition Unit
PR – Protection Relays
RTU – Remote Terminal Unit
SOE – Sequence of Events Recorder

switching status caused by protective relay operations. However, it was neither possible to find a location of the fault on the faulted line, nor was it possible to analyze the sequence of operation of circuit breakers based on the contacts alone. This was the main reason why the second category of approaches was introduced [4]. Inclusion of analog signals and comparative analysis of contacts with respect to the time when analog signals experienced a disturbance, enabled a far more detailed analysis. The analog signals provide temporal reference so that sequence of events can clearly be established. Also, the analog signals provide additional information about the reasons for contact changes so that the hypothesis for the analysis can be defined more precisely. Further discussion in this section is related to the possible implementation approaches in the second category where the analysis is based on both analog signals and contacts.

Study of the substation equipment characteristics indicates that digital fault recorders (DFRs) are the most appropriate sources of analog signal and contact data for the fault analysis application. The reason is their accurate data sampling which is also synchronized across channels of a recorder. The question remains regarding choice of functions that can be implemented on DFRs to facilitate fault analysis. Several functions of interest can be identified as shown in Figure 2.

The functional organization given in Figure 2 demonstrates variety and complexity of possible fault analysis implementation approaches. The simplest implementation may be to detect a fault using samples of analog signals and based on this to analyze circuit breaker operation. The most complex approach is to utilize samples of analog signals to emulate the entire logic of a protection relay, as well as the one of a fault locator. This, combined with detailed analysis of sequence of operation of associated circuit breakers and communication channels, would provide the basis for a most comprehensive fault analysis.

A final note relates to location of DFRs and their use in collecting substation data. A typical approach in the utilities is to locate DFRs in several strategic substations. Furthermore, due to the limited number of DFR channels available,

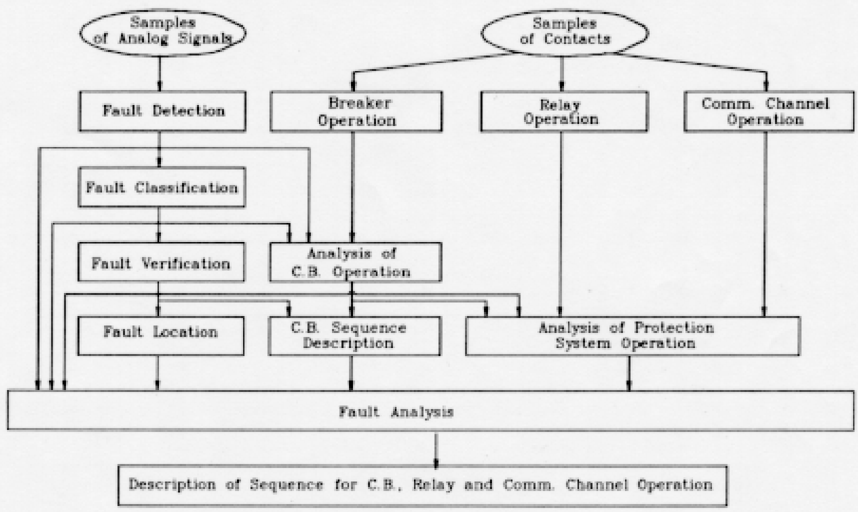

Figure 2. Fault Analysis Function

only some of the most important signal sources from a given substation are connected. Therefore, the existing practice does not allow for collection of all data at all substations. Also, data sampling at different DFRs is typically not synchronized with a common time reference. This generates a need to perform additional processing if data sampled at different locations need to be combined and/or compared.

HOUSTON LIGHTING & POWER EXPERT SYSTEM SOLUTION

This section illustrates how a new expert system approach can be utilized for fault analysis. Details of this solution have been published previously [4–6]. A description given below provides some basic characteristics of a solution that has been utilized for automated fault analysis at Houston Lighting & Power Company.

An Expert System block diagram is shown in Figure 3.

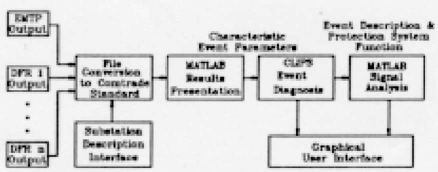

Figure 3. Expert System Block Diagram

The data conversion block translates the format of data generated by the Electromagnetic Transient Program (EMTP) [7] and different Digital Fault Recorders (DFRs) into a format suitable for analysis performed by a commercial signal processing package MATLAB [8]. Additional substation description interface is developed to make up for insufficient EMTP/DFR configuration data. A MATLAB program analyzes raw data to provide parameters required for the diagnostic process. CLIPS, an expert system shell [9], takes data from MATLAB to make final conclusions on the fault detection and diagnosis. EMTP is used to generate test data through simulation while DFR are used to collect actual data in a substation.

Event diagnosis in CLIPS is performed by using rules in forward chaining mechanism. This mechanism uses analog signal and protection system operation parameters calculated in MATLAB. These parameters are voltage and current RMS values, as well as breaker, relay and communication contacts for the transmission line that experiences the largest current disturbance. This data are extracted from the set of substation transmission line data by MATLAB. It also distinguishes the three characteristic time intervals of the event. These time intervals are the predisturbance, disturbance, and post disturbance. The voltage and current RMS values for the three time intervals are calculated as the analog signal parameters. MATLAB identifies incidence of breaker and relay change of status as protection system parameters. It also analyzes the communication signal operation intervals to identify the communication protection system parameters.

Result presentation and Graphical User Interface (GUI) blocks serve as a final Expert System output. There are several different levels of information that are given through GUI. All together, this information includes a complete step–by–step reasoning process performed by the CLIPS shell, as well as a plot of voltage and current waveforms for a transmission line experiencing disturbance, including circuit breaker and communication channel contacts.

There are as many DFR file formats as there are DFR manufacturers. This represents serious problems when developing automated (computer aided) mechanisms to acquire the desired data and to put it in a suitable format. This has generated the need for a standard format for the exchange of data. Such a standard, called IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems has recently been approved [10]. It defines sources of transient data, data exchange medium, data exchange sampling rates, files for data exchange, and organization of transient data.

PERFORMANCE DEMONSTRATION

An Expert System prototype has been tested using DFR files captured at a substation with a one–line diagram shown in Figure 4.

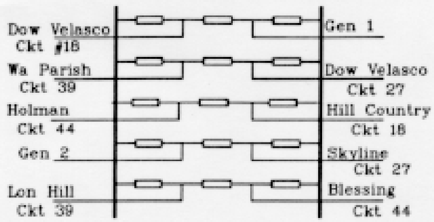

Figure 4. A One–Line Diagram for the STP Substation

As an example, results of an analysis for phase–to–ground fault on circuit 39 are presented in Figure 5. Presentation of analog waveforms can be added to illustrate the results. The MATLAB package is used for this purpose.

Further evaluation of the expert logic is under way by using a remote connection between the STP substation and Texas A&M University. This configuration is shown in Figure 6. Eventually, the expert system will be located at STP substation and the link to Texas A&M University will cease to exist. In that case, the short messages similar to the ones shown in Figure 5 will be sent to Houston Lighting & Power Company in Houston. This will replace the existing practice where a stream of recorded data is sent from STP substation to HL&P once an operator dial–up call from HL&P offices is placed. The new automated system will only need several minutes for expert system to complete the analysis locally at the substation. Potential savings in time and manpower are almost obvious.

FUTURE DEVELOPMENTS

Recent introduction of a new digital recorder incorporating receivers for the Global Positioning System (GPS) of satellites has opened new possibilities for fault analysis improvements using synchronized sampling [11]. If such recorders are available at each substation, then extremely accurate fault location can be implemented providing major enhancement in the fault analysis process [12]. Since the ultimate goal of fault analysis is to locate a fault, the improved fault location will represent the most desirable approach. A typical set–up for the equipment in use for such an implementation is shown in Figure 7.

```
****Welcome to the Brain of the Fault Detection and****
****Classification Expert System****
****EVENT DESCRIPTION USING ANALOG DATA****
PH39 is the circuit with largest current disturbance.
The Disturbance is a ground fault.
The disturbance is a line C to line A to ground fault.
The fault is either cleared by the protection system of
another substation or it is a self clearing fault
****PROTECTION SYSTEM OPERATION ANALYSIS****
Protection system behaved correctly.
It did not operate at this substation,
for a fault within another section.
Thank you
```

Figure 5. Event Description Given by the Expert System

The synchronized sampling approach to data acquisition has a number of advantages over the existing one. First, the improved fault location is made possible. Secondly, merging of files from different DFRs is quite easy due to the absolute (synchronized) time reference used to record data. Finally, this type of recorder performs very accurate signal sampling which facilitates implementation of several other functions such as phasor measurements [13], revenue metering [14], tracking of frequency and its deviation [15], measurements associated with power quality assessment [16], and measurements associated with power system disturbance monitoring and analysis [17]. Table II gives a summary of the mentioned measurements that can be implemented to enhance overall analysis of events recorded by these devices.

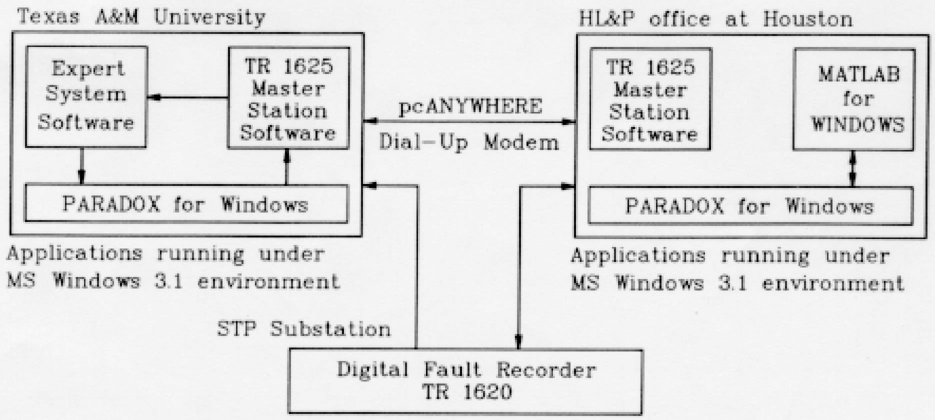

Figure 6. Initial ES Testing Using Direct Connection to STP Substation

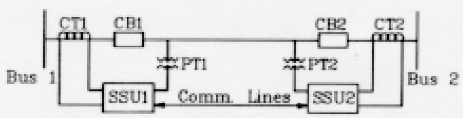

Figure 7. Fault Recorders with Synchronized Sampling

Table II. Measurements for Enhanced Event Analysis

Measurement	Function
Fault Location	Confirmation and location of a fault
Fault Detection	Identification of a faulted line
Fault Classification	Determination of a type of fault
Frequency	Detection of over/under frequency condition
Phasors	Detection of an Out-of-Step condition
Harmonics/ Subharmonics	Detection of presence of harmonics/subharmonics
Power	Measurement of active/reactive power
Spikes	Detection of switching transients

Therefore, future developments of fault analysis techniques may include use of synchronized sampling to improve fault location, overall system data base and performance of various measurement functions.

CONCLUSIONS

This paper illustrates new approaches to Expert System utilization for fault analysis. The main conclusions are that:

- existing approaches using contact data have limited capabilities in locating fault and analyzing protection system operation,
- new approaches based on use of DFR data provide improved performance in analysis of faults, as well as circuit breaker, protection relay and communication scheme operation,
- future trends in the field of fault analysis may include use of synchronized sampling which provides extremely accurate fault location, capability of easy merging of data from various substations and improved accuracy of various measurement functions.

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REFERENCES

[1] M. Kezunović, "Implementation Framework of an Expert System for Fault Analysis," *Third Symposium on Expert System Applications to Power Systems*, Tokyo/Kobe, Japan, April 1991.

[2] B. F. Wallenberg, T. Sakaguchi, "Artificial Intelligence in Power System Operations," *Proceedings of the IEEE*, Vol. 75, No. 12, December 1987.

[3] *Proceedings of the Symposia on Expert system Applications to Power Systems:* First–Stockholm/Helsinki, 1988; Second–Seattle, 1989; Third–Tokyo/Kobe, 1991; Fourth–Melbourne, 1993.

[4] M. Kezunović, et. al., "An Expert System for Substation Event Analysis," *IEEE PES Winter Meeting*, Paper No. 93 WM 057–0 PWRD, New York, February 1993.

[5] M. Kezunović, P. Spasojević, "An Expert System for DFR File Classification and Analysis," *Fourth Symposium on Expert System Applications to Power Systems*, Melbourne, Australia, February 1993.

[6] M. Kezunović, et. al., "Digital Fault Recorder File Classification and Analysis Using Expert System and Signal Processing Techniques," *Texas A&M Relay Conference*, College Station, Texas April 1993.

[7] *Electromagnetic Transient Program – Workbook*, Electric Power Research Institute, Palo Alto, California, September 1986.

[8] *PC–MATLAB–Users Guide*, The Mathworks, Inc., South Natick, Massachusetts, May 1989.

[9] *CLIPS – Reference Manual*, Artificial Intelligence Section, Johnson Space Center, Houston, Texas, September 1987.

[10] *IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems*, Institute of Electrical and Electronic Engineers, Inc., New York, New York, June 1991.

[11] Macrodyne, Inc., "Phasor Measurement Unit–Model 1690," *Application/Performance Data Sheet*, 1993.

[12] M. Kezunović, et. al., "Accurate Fault Location Using Synchronized Sampling at Two Ends of a Transmission Line," 11^{th} *Power Systems Computation Conference*, France, September 1993.

[13] IEEE Power System Relaying Committee, "Synchronized Sampling and Phasor Measurements for Relaying and Control," Working Group Report, *IEEE PES Winter Meeting*, Paper No. 93WM 039–8 PWRD, New York, February 1993.

[14] M. Kezunović, et. al., "New Approach to the Design of Digital Algorithms for Electric Power Measurements," *IEEE Trans. on Power Delivery*, Vol. 6, No. 2, April 1991.

[15] M. Kezunović, et. al., "New Digital Signal Processing Algorithms for Frequency Deviation Measurement," *IEEE Trans. on Power Delivery*, Vol. 7, No. 3, July 1992.

[16] M. Kezunović, et. al., "Digital Signal Processing Algorithms for Power Quality Assessment," *IEEE IECON '92*, San Diego, November 1992.

[17] M. Kezunović, et. al., "New Digital Signal Processing Algorithms for Power System Disturbance Monitoring and Analysis," *Intl. Conf. on Computer Applications in Industry and Engineering*, Honolulu, Hawaii, December 15–17, 1993.