PRACTICAL APPLICATIONS OF AUTOMATED FAULT ANALYSIS

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Abstract: This paper describes a new concept of automated fault analysis where fault transients and changes in power system equipment contacts are processed on-line. This allows faster confirmation of correct equipment operation and detection of unexpected equipment operations, as well as increased accuracy of fault location and analysis. The paper discusses two independent utility examples that illustrate automating some aspect of the fault analysis process. One approach is the substation level analysis, where local digital fault recorder (DFR) data is processed at the substation to obtain accurate fault location and analysis. Another approach is DFR data analysis at the master station location, where all DFR data files from remote locations are concentrated and processed.

Key Words: Fault Analysis, Intelligent Systems, Digital Fault Recorders, Expert Systems

I. INTRODUCTION TO THE PROBLEM

Development of new technologies such as intelligent systems and synchronized sampling as well as increased utility deregulation and competition are leading to the introduction of new applications and solutions in the fault analysis area.

The early approaches to fault analysis using intelligent techniques were related to alarm processing in a Supervisory Control and Data Acquisition (SCADA) system [1]. At that time, expert system techniques were utilized to implement an automated analysis of alarms [2]. The SCADA based solutions did not have the capability to calculate fault location, and processing of analog waveforms was not done due to the lack of sampled waveform data. Further improvements of the overall solution were achieved using neural network (NN) implementations [3,4].

A study of the possible approaches to fault analysis using digital fault recorder (DFR) data revealed some advantages due to the ability to calculate fault location and correlate waveform samples with protective relay and circuit breaker contact operation. This has enabled a new approach to fault analysis to be implemented using expert systems and DFR data [5-7]. Use of neural nets for fault detection and classification was also investigated to enhance the overall fault analysis solution [8,9].

This paper summarizes results from two different projects aimed at automated fault analysis. The two projects demonstrate possible approaches to automated fault analysis using DFR data and expert systems. A set of conclusions and related references are given at the end.

II. A CASE STUDY OF RELIANT ENERGY HL&P

Occurrence of a fault on a major transmission line may endanger the operation of a bulk power system and potentially lead to costly outages. If the fault analysis results are not available to system operators shortly after the fault occurred they might not be able to reach an optimal decision regarding the restoration of a line. In the era of increased competition between utilities due to the open access and retail wheeling, any unnecessary delay of energy supply restoration compromises a utility's competitive position.

The project described in this section is aimed at utilizing existing DFR data to provide a system dispatcher with accurate and timely information regarding the fault type and fault location, as well as an analysis of the operation of protection system and related equipment. The dispatcher can use this information to decide if a transmission line should be restored back to service or a maintenance crew dispatched.

2.1 System Architecture

The block diagram of the system that was developed is shown in Figure 1. The expert system communicates with DFR over a high-speed parallel link. It interrogates the DFR for new recordings on a continual basis. A new data file is copied from a recorder and immediately analyzed. The analysis report is created and faxed to the system dispatcher and to the protection engineer's office. The whole process takes less than a minute, so valuable information is available to the system dispatcher in a relatively short period of time after a fault was recorded by the DFR.

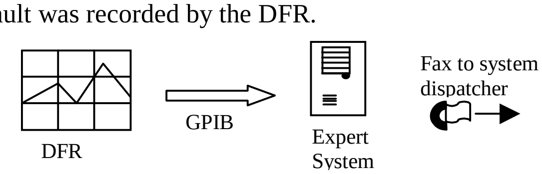

Figure 1. Diagram of the Substation Analysis System

The analysis report typically contains the following information:

- Event date/time stamp and DFR identification
- Fault type, fault location, and transmission line involved

Table I. Behavioral Patterns of the Basic Parameters

Event Type	0 Sequence Current	Faulted Current	Unfaulted Current	0 Sequence Voltage	Faulted Voltage	Unfaulted Voltage	Line Voltage
a - g	$I_0 > .2I_a$	$I_a > 1.4I_p$	$I_{b,c} < .331_a$	$V_0 > .04V_n$	$V_a < .9V_n$	$V_{b,c} > .96V_n$	V_{ab} □ V_{ca}
a - b	$I_0 < .01I_a$	$I_a > 1.4I_p$ $I_b > 10I_p$	$I_c < 11_a$	$V_0 < .01V_n$	$V_a < .8V_n$ $V_b < .7V_n$	$V_c > .99V_n$	$V_{ab} < .8V_{luf}$
a - b - g	$I_0 > .1I_a$	$I_a > 1.4I_p$ $I_b > 10I_p$	$I_c < .11_a$	$V_0 > .05V_n$	$V_a < .8V_n$ $V_b < .8V_n$	$V_c > .98V_n$	$V_{ab} < .8V_{luf}$
a - b - c	$I_0 < .03I_b$	$I_f > 10I_p$		$V_0 < .01V_n$	$V_f < .8V_n$		$V_{lf} < .8V_{ln}$
a - b - c- g	$I_0 < .03I_b$	$I_f > 10I_p$		$V_0 < .01V_n$	$V_f < .8V_n$		$V_{lf} < .8V_{ln}$

- Relay tripping times, breaker opening times, and carrier signaling
- Snapshot of RMS values for selected analog channels

The fault analysis logic incorporated in the expert system's knowledge base relies on signal processing algorithms to extract aggregate parameters such as RMS values for phase currents and bus voltages from samples recorded by DFR. These parameters are then passed through the set of rules that represent relationships between system variables during different fault (or normal) operating conditions. The mathematical relationships between various parameters for certain fault types are shown in Table I [5].

2.2 Knowledge Acquisition and Rule Definition

The knowledge necessary for disturbance analysis was acquired by interviewing experts (protection relay engineers) and by using an empirical approach based on EMTP simulation studies. The reasoning process includes the following steps: fault detection, fault classification, event analysis, and protection-system and circuit-breaker operation analysis.

Fault detection and classification can be described by the following procedure, as outlined by the experts:

- Fault inception instant is detected by looking for the abrupt change in signal waveforms.
- Voltage waveforms are checked for a change in the fundamental harmonic amplitude. A voltage decrease indicates the possible faulted phases.
- Current channels of the phases that experienced a significant voltage decrease are checked next. The current that experienced the greatest amplitude increase indicates the probably faulted circuit.

The overall change in voltage and current waveforms indicates the type of fault (e.g., phase A to ground). It also points to other characteristics of the fault and the behavior of the protection system (fault clearing, reclosing).

Event and protection system operation analysis includes the following checks:

- Relay and breaker contacts' state is checked for a change. A status change is an indication that the protection system has detected a fault.
- If the protection system operation is detected and the presence of a fault is not identified, it is an indication of a protection system misoperation.
- If a fault is detected and there is no protection system operation, it is an indication of a possible protection system failure.

The reasoning required to perform classification and analysis of the event is implemented by using a set of rules. The reasoning process is separated into two stages. In the first stage, the system reasons on the basis of the analog-signal parameters, and in the second step, it reasons by using the protection-system parameters. Analog-signal and protection-system parameters are obtained by processing the recorded samples and extracting the relevant features of the signals recorded on the line that had experienced the largest disturbance.

A typical set of rules based on the analog parameters is shown in Figure 2. A sequence of checks is indicated by the circled numbers next to the rule definitions.

This set of rules represents the application's knowledge about the operation of a power system section in the form of "rules of thumb". The rule base is expandable and can be change over time, when a better understanding of particular operations of power system equipment becomes available.

To facilitate modularity and extensibility of the analysis logic, a "C Language Integrated Production System" (CLIPS) expert system tool was embedded in the application. This tool allows addition of new rules which specify a new set of actions to be performed for a given power system operating condition.

Figure 3 shows an example of a CLIPS rule to determine if particular conditions for a phase-to-ground fault are met. The exact thresholds (multiplication coefficients) will change from

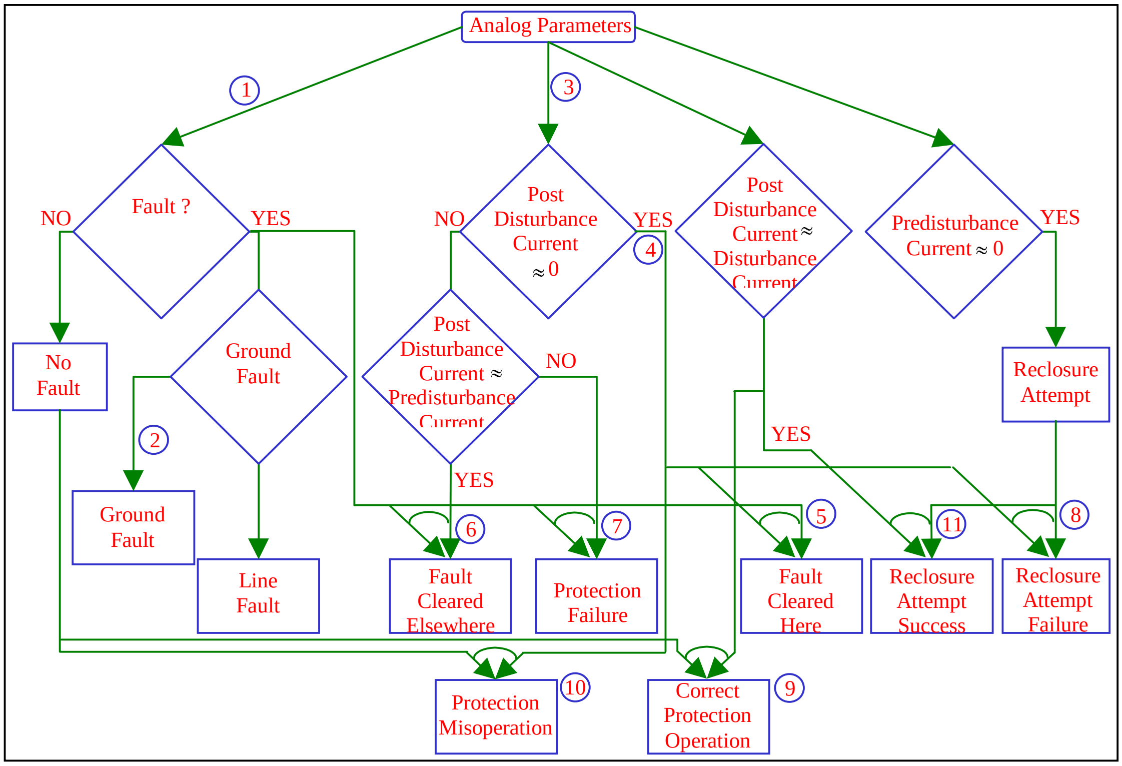

Figure 2. Rules for Fault Detection, Classification, and General Event Analysis Using Analog Parameters

substation to substation, and may need to be determined by trial and error as well as modeling and simulation.

```
(defrule  AG_fault
    (Ipre  ?Iap ?Ibp?Icp ?I0p)             (Iflt ?Ia ?Ib ?Ic ?I0)
    (vpre ?vap ?vbp ?vcp ?v0p)             (vflt ?va ?vb ?vc ?v0)
    (vlp ?vabp ?vbcp ?vcap)                (vl ?vab& ?vbc ?vca)
    (test (> ?I0 (* 0.20 ?Ia )))           (test (> ?Ia (*1.40 ?Iap)))
    (test (< ?Ib (* 0.33 ?Ia )))           (test (< ?Ic (* 0.33 ?Ia )))
    (test (> ?v0 (* 8.00 ?v0p)))           (test (< ?va (* 0.90 Ivap)))
    (test (> ?vb (* .96 ?vbp)))            (test (> ?vc (* 0.96 ?vcp)))
    (test (< (abs (-?vb ?vc))  (* .05 ?vbp)))
    (test (< (abs (- ?vab ?vca))  (* .2 ?vabp)))
    (test (< (abs (-?vbc ?vbcp)  (* .2 ?vbcp)))
=>
    (format t "AG_Fault fired%n")
    (assert (FaultType "phase A to ground fault")) )
```

Figure 3. Example of a CLIPS Rule

The expert system software is fully automated. Once configured, no operator interaction with the system is needed The system reports is operating status on a daily basis by sending a fax message to the dispatcher's and protection engineer's office.

III. A CASE STUDY OF TXU ELECTRIC

The objective of this research project was to streamline DFR data files that are coming from many different locations and archive them on a corporate LAN using certain classification criteria. The basic data flow diagram is shown in Figure 4. The DFR Master Station PC's #1 through #3 are responsible for communicating with remote recording units via dial-up modem lines. The Master Station units can be configured to automatically poll remote recorders on periodic basis and retrieve new events, or substation DFRs can be setup to automatically call a Master Station when they have a new event to report. For this project, the second option was used.

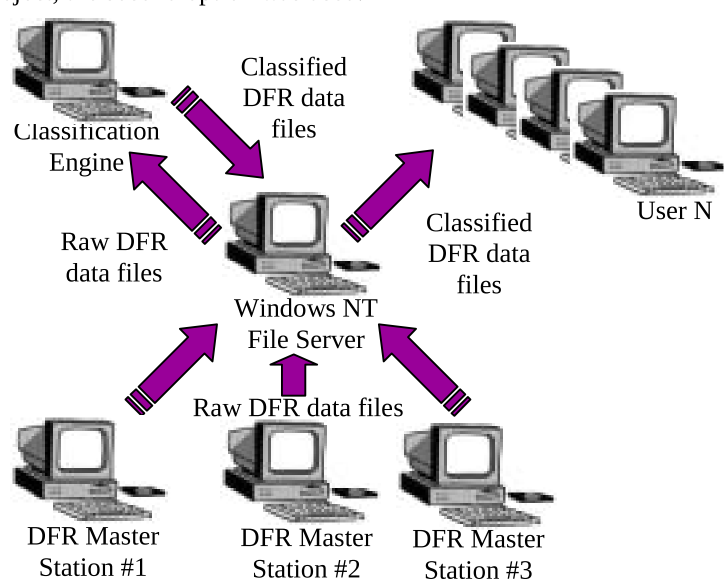

Figure 4. Classification System Block

It is worth mentioning, at this point, that this system is configured to classify files coming from DFRs made by two different vendors. The classification system has been generalized to allow easy incorporation of additional vendor's digital recording systems, as long as the particular DFR vendor provides DFR file format description. For utilities that may have DFRs from multiple vendors, this classification system feature provides a common platform for fault analysis and the distribution of results. In addition, the common platform eliminates the need to train employees to use multiple DFR manufacturer analysis packages.

3.1 The Classification Engine

To facilitate the classification process as well as distribute classification results across the corporate Intranet, a dedicated File Server PC and a Classification Engine are secured. The Classification engine diagram is the “brain” of the system. It monitors assigned incoming file directories on a File Server and detects any new DFR data file that has been copied from Master Stations. These new files are processed using built-in logic to produce a classification report. Finally, the Classification Engine automatically converts the raw DFR data file into the COMTRADE format [10] and copies it with associated classification report to an assigned directory on Windows NT File Server.

The File Server is a repository of both the raw DFR data files in its native format and the processed DFR files in the COMTRADE format. The easy access to the processed DFR files is facilitated by archiving all data files into three categories (high, medium and low priority) based on certain criteria. A separate software package for viewing the processed DFR files is available. This package provides an integrated environment for displaying both the conclusions about the analysis of a selected DFR file, as well as graphics in the form of analog and digital traces.

One of the tasks of the Classification Engine is to reduce the time that system protection personnel spend on manual examination and archival of DFR records. This system automatically classifies and filters DFR records based on the following broad criteria:

- The fault condition exists and clearing time is satisfactory.
- The fault condition exists and clearing time is longer than expected.
- The fault condition exists and breaker restrike and/or ferro-resonance occurs during fault clearing.

Table II shows the list of signals that are used for the DFR file classification logic. If the signal is not monitored in a particular DFR configuration, associated classification logic cannot be implemented. In the case where only the two phase currents plus residual current are monitored, the third phase current will be calculated automatically by the Classification Engine.

The following parameters are extracted and/or calculated from every DFR record:

- Relay trip times and relay pick-up time
- Breaker open/close times and breaker pick-up time
- Breaker failure start times
- Carrier start/receive times
- Calculated fault inception time

The classification logic is based on the analysis of the above parameters. The following are the events that can be recognized and flagged by the system:

- Slo relay clearing
- Breaker failure or slow breaker clearing
- Breaker restrike
- Carrier misoperation
- PT Ferro-resonance
- Reclosure failure, Line lockout

Table II. Input Signals Used by Classification Engine

Digital	Primary and backup relay trip	
	Breaker open position	
	Breaker close position	
	Breaker failure (BF) contact	
	Carrier Start and Carrier Received contacts	
Analog	At least two phase currents	(Ia, Ib,Ic)
	Residual current	(Ir)
	All three phase (bus side) voltages	(Va, Vb, Vc)
	Residual (neutral) voltage	(Vr)

The Classification Engine keeps a detailed log of the system events during its operation. System events such as the names of the corrupted DFR files, or names of the incomplete DFR files are time stamped and recorded. The logging capabilities help the administrator troubleshoot the system operation on a daily basis.

The Classification Engine archives all incoming DFR files into three categories depending on the type of the event. These categories are High, Medium, and Low priority (see Figure 5). Events such as the normal fault clearing, or reclosure success will be categorized as high priority events and archived in the High priority folder on the central file server. Events such as the normal fault clearing, or reclosure success will be categorized as the medium priority. And finally, the events such as no operation will be stored in the Low priority folder.

3.2 The Report Viewer

The Report Viewer is the Windows 95 client software used for accessing classification reports form the central file server. The module has an extensive graphical user interface (GUI) that allows users to access DFR reports and data files either locally (when directly connected to corporate LAN) or remotely (when connected to corporate LAN over a dial-up modem line). The Report Viewer application's main window consisting of three parts: network/local director display, waveform display, and classification report display.

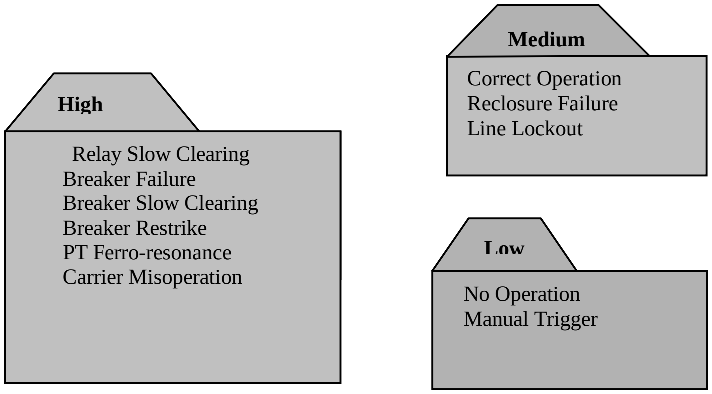

Figure 5. Classification Logic Categories

The user may choose the event priority that he/she wants to access and display in the directory view. The default priority is High. The network/local directory display contains three columns: name of the DFR that recorded particular event, date/time stamp and short description of the event. For accessing the data over WAN (via dial-up connection), the application provides a caching function, similar to Internet browsers. This means that the data once down-loaded will be saved in the caching directories on the local drive, thus eliminating the need to retrieve the same event files over the WAN multiple times. In addition, the caching function enables the user to view the downloaded data files off-line.

The textual display of the Report Viewer presents the following information to the user (Fig. 6):

- Event Date/Time Stamp
- Event Type (e.g. breaker failure, etc.)
- Event Size (prefault, fault, postfault cycles)
- DFR Type and Recorder ID
- Breaker Operation Time
- Operation of Carrier Channels
- RMS values for associated Breaker ID's analog channels per cycle for every cycle in the record (the display will be color coded for prefault, fault and postfault intervals)
- Harmonic content of associate analog channels in a tabular form.

The waveform display of the DFR file presents graphs of analog and digital signals. This display has the following properties:

- Selectable DFR channels to display
- Tickmarks on the x and y axis
- Auto-scalable x and y axis
- Selectable time axis (milliseconds, cycles, or samples)
- Selectable waveform coloring
- Colored markers on the analog traces where the digital channel operation occurred
- Zooming capability

- Legend containing channel description and values of analog and digital signals at cursor position
- Measure of the time span between two points on the screen
- Waveform printing and print preview

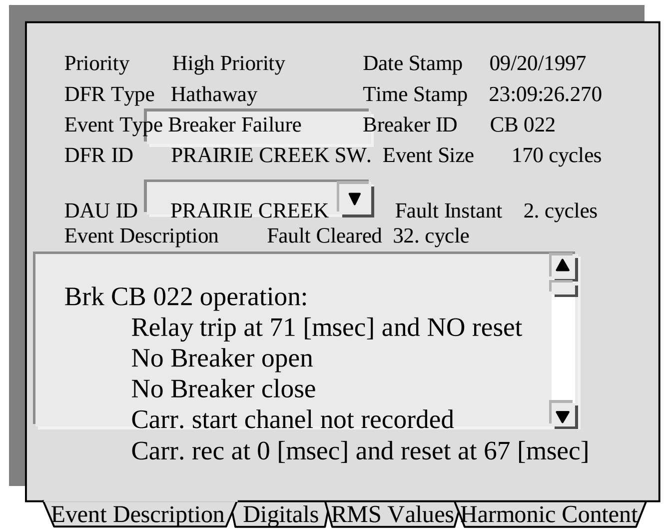

Figure 6. The Report Viewer Text Display

IV. CONCLUSION

This paper has introduced a concept of automated fault analysis utilizing DFR data collected at various substations. A variety of solutions can be implemented using existing advanced technology. The following are the projects and related benefits that are being implemented by Texas A&M University and its utility partners:

- High-speed automated substation based fault analysis using DFR data.
- Integrated system wide automated analysis of DFR data from different DFR systems.

V. ACKNOWLEDGEMENTS

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