

# Automated Analysis of Protective Relay Operation

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**Abstract** - This paper describes possible approaches in implementing a system solution to automate analysis of the fault events that may be recorded by several DFRs. One approach involves automated analysis at a substation level, where DFR records are processed locally and then transferred to central location for further analysis. The other approach involves centralized analysis where all DFR recordings are grouped at a single location and then processed.

**Keywords:** Automated fault disturbance analysis, digital fault recorders, protective relays, rule-based systems, neural nets

## I. Introduction

Digital fault recorders (DFRs) are extensively used by some utilities to record voltages, currents and equipment contacts during power system faults. Typically, the disturbance causes DFRs to trigger collecting several cycles of sampled waveform data together with related contact status. The sampled data is stored locally in the recorder until it is either automatically downloaded or manually transferred to a central location. This data transfer is controlled through the Master Station (MS) software located on a PC at the central location. Once the data is made available at the central location, protection engineers are analyzing this data in order to characterize the fault event and assess operation of the protection system.

One of the main goals of the new software developments is to automate the analysis process so that the overall analysis time is reduced. This paper describes possible approaches in implementing a system solution to automate analysis of the fault events that may be recorded by several DFRs.

The paper starts with a description of an existing software solution that automates the analysis at the substation level. The next section describes possible system-wide solutions. The analysis logic that can be implemented in the system-wide solutions is summarized at the end. Some future developments for further improvements of the analysis logic are discussed at the end.

## II. Substation Based Solution

Houston Lighting & Power (HL&P) company contracted Texas A&M University (TAMU) several years ago to develop a system for automated analysis of DFR recordings for one of their substations. The development has been com-

pleted and system commissioned in 1995. This section summarizes the system configuration and main features [1].

Figure 1 shows the main hardware items and data flow. Local computer interrogates DFR, at pre-specified time intervals, looking for a new record. The communication between DFR and PC is done via high speed GPIB link that enables transferring of complete records within 20 seconds time intervals. Once the record is archived at local PC, the analysis takes place. Depending on the record size, the analysis is completed in 40 to 60 seconds. After completion of the analysis, the fax message is created and sent to several locations within the company. System dispatcher receives the first fax within 2 minutes after event has been transferred to the PC.

The system, once installed and configured, is completely automated; no operator intervention is needed. This system has "system alive" function that reports its operating status in prescribed time intervals, usually once a day, by faxing a message to corporate office.

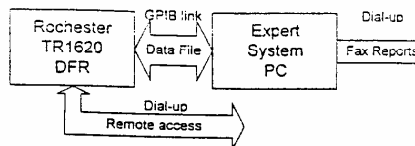


Figure 1. Analysis system configuration in a substation

The system's software consists of several modules. These modules include programs for:

- communication with DFR
- event file archiving
- signal processing of analog and digital channels recorded by DFR
- rule base expert system for analysis and event classification
- faxing analysis reports to remote sites

An example of a typical analysis report that is being faxed is given in Table I. First section of the report presents general information about recorded event. The second and third sections contain information about fault type, transmission line involved and estimated fault location. The next section presents overview of protection system operation with operating times for relays and circuit breakers. The last section shows values for analog waveforms of a faulted transmission line before, during and after disturbance.

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TABLE 1. Analysis system configuration in a substation

EXPERT SYSTEM STATION REPORT				
Date/Time Stamp of Event: 04/04/95, 12:44:44 938				
Event number: 017		Sample rate: 5.99 [kHz]		
Machine name: S.T.P.		Serial number: 20299		
Number of pretrigger samples: 1198 (12.0 cycles)				
Total number of samples: 2926 (29.3 cycles)				
Size of the event in tracks: 10 (320Kb)				
EVENT DESCRIPTION				
D. Velasco Ckt #27 is the circuit with largest current disturbance.				
The disturbance is a phase B to ground fault.				
The fault is cleared by the protection system at this substation.				
FAULT LOCATION				
Fault is located 21.54 miles from this substation.				
PROTECTION SYSTEM OPERATION ANALYSIS				
Backup relay operation starts at 0.0337 sec [2.0202 cycles]				
and ends at 0.0487 sec [2.9202 cycles].				
The middle 52B contacts operate at 0.0605 sec. [3.63 cycles].				
The bus 52B contacts operate at 0.0537 sec. [3.2202 cycles].				
The bus breaker status change after trip is applied is 1.2 [cyc].				
The middle breaker status change after trip is applied is 1.6 [cyc].				
LINE CURRENTS AND VOLTAGES				
	Prefault	Fault	Postfault	
IO	0.0087	24.19	0.001	[kA]
Ia	0.2076	0.801	0.000	[kA]
Ib	0.1868	22.83	0.000	[kA]
Ic	0.1672	0.272	0.004	[kA]
VO	0.0008	0.086	0.001	[kV]
Va	283.70	272.5	282.2	[kV]
Vb	283.90	106.4	282.8	[kV]
Vc	284.70	272.7	283.6	[kV]
Vab	491.20	327.6	488.8	[kV]
Vbc	493.10	342.6	491.5	[kV]
Vca	492.05	483.5	489.4	[kV]
All above values are peak values.				

During the initial period of field testing, system was calibrated and adjusted to the specific system conditions at selected substation. Since the analysis software includes full-blown expert system shell, the addition of new rules to cover changing power system conditions was easy.

Test Laboratories International Inc. obtained license rights for the software from Texas A&M University with intention to further enhance and commercialize existing technology [2]. Some of the new ideas and developments in this area are presented in the following sections.

### III. Advanced System-wide Solutions for Automated Fault Analysis

The following list outlines main requirements of an automated system-wide for analysis of DFR recordings:

- **DFR file analysis logic at a system level.**  
It correlates data files from all DFRs triggered by the same event. The analysis steps include disturbance detection, identification of the transmission line(s) involved, fault type classification, and calculation of fault location as well as analysis of operation of protection relays and associated circuit breakers.

- **Central database for archiving of analysis results.**  
The analysis results are stored at a central database and made readily available to different users over the LAN and via Internet.
- **Automatic notification via E-mail and faxes.**  
The analysis results are E-mailed or faxed automatically to all specified recipients.

The above mentioned requirements can be met in two different ways. One way is to download events to a central location and then analyze them. The other way is to process events locally at substations and then communicate results of the analysis to the central location for further processing.

The benefit of the first solution is lower cost of hardware (one PC is needed at a central location for analysis purposes, but no PCs at substations are required). The shortcoming of this solution is the time delay associated with slow data transfer of lengthy DFR files over a modem dial-up line, which effectively makes the analysis results provided by this system delayed. This may mean that the analysis results are generated with too much of a delay to be useful for on-line action by the system dispatcher.

The benefits of the second solution are high speed local event analysis and reduced data communication between DFR and a central location. This solution will provide system dispatcher with event analysis minutes after the event was recorded. The shortcoming is higher cost of hardware (i.e., PC at each substation is needed).

Two different system implementation options can be identified as follows:

- DFR data files downloaded and analyzed at a central location
- DFR data files first analyzed locally at substation and then results transferred to central location for further processing

#### A. Centralized Analysis

Figure 2 shows hardware configuration consisting of three PCs. DFR Master Station PC communicates with the DFRs in the field over one or more dial-up lines. Transferred DFR event files are automatically archived on a separate PC (DFR Events Archive) over corporate LAN.

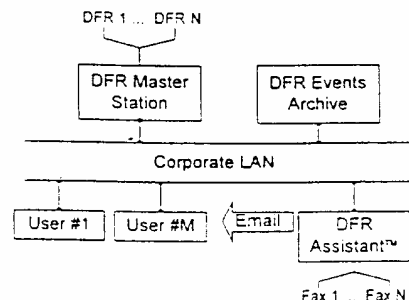


Figure 2. Possible configuration with centralized analysis

server, processes them and returns the results of analysis back to the common database residing on the server. In addition, DFR Assistant sends out Email and fax notifications to specified recipients. A version of this approach is presently being implemented for TU Electric in Dallas, Texas. [3]

## B. Substation Level Analysis

Figure 3 shows a block diagram for this approach. This solution requires a local PC connected to DFR at each substation. Typically a low cost PC configuration (<\$1,500) can be used for this purpose. These local PCs retrieve and process DFR data files almost immediately after they are recorded. The event analysis is based on the data available at local substation and analysis reports are available in less than a minute. Analysis reports are, then, communicated to the PC residing at a central location (DFR Assistant™) for further processing. This processing includes correlating the analysis reports coming from various substations and generating a summary report for a given event.

A version of this approach is presently being implemented for Houston Lighting & Power company in Houston, Texas.

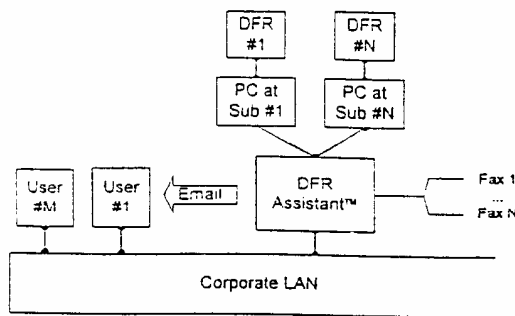


Figure 3. Possible configuration with substation level analysis

## IV. The Analysis Logic and Related Input/Output Data

The task of the analysis logic in each of before mentioned configurations is to answer the following questions:

- Which DFR has triggered and recorded waveforms for a particular power system disturbance?
- What was the disturbance and what lines were affected?
- Where is the location of the fault (in the case the disturbance is a fault)?
- Did protection system operate correctly?

The analysis logic for classification of DFR recordings in all of before mentioned cases consists of the following steps:

- identifying the faulted transmission line
- identifying all records pertaining to the same event
- correlating and analyzing all records identified in the previous step

several algorithms that take into consideration both analog signals and digital contacts. The analog waveforms are divided into three sections. One section corresponds to the pre-fault, one to fault and one to postfault conditions. Similarly the status change of digital channels is extracted from the record and correlated to the calculated fault inception time.

The following types of input signals are used by the analysis system:

- Phase currents (A, B, C, 0)
- Bus or line voltages (A, B, C, 0)
- Relay trip contacts
- Breaker open/close position
- Pilot channels (send, receive, stop)

Figure 4 shows top level window of DFR Assistant™ [2]. The left hand side presents information about configured DFRs, their connections (e.g., buses, transmission lines), while the right hand side lists DFR recordings that are transferred from the remote substations. User can easily access database of processed events by clicking on the toolbar buttons (denoted by H, M, L). Clicking on any of these buttons brings contents of either high, medium or low priority directories. The filtering logic for storing analysis reports into these three directories is based on the following criteria:

- **High Priority**
  - ♦ fault confirmed; relay did not operate (failure)
  - ♦ no-fault confirmed; relay operated (misoperation)
  - ♦ fault confirmed; breaker restrike occurred
  - ♦ relay trips and breaker does not open
  - ♦ relay trips and breaker opens slowly
  - ♦ relay trips and carrier signaling incorrect
  - ♦ ferro-resonance condition occurs
  - ♦ none of the above (unable to classify DFR record)
- **Medium Priority**
  - ♦ fault confirmed and backup relay trips instead of primary relay
  - ♦ relay trips but relay pick-up time slow
- **Low Priority**
  - ♦ correct fault clearance by the protection equipment
  - ♦ DFR manual triggering

Figure 5 shows the window used for viewing of the analysis reports. This window displays the same type of information as given in Table 1 using different format.

## V. Further Developments

This section briefly describes some of the ideas presently being investigated regarding the enhancements of the existing software for automated analysis.

### A. Fault Detection and Classification

As described in previous sections, the knowledge base implemented in the automated analysis system performs the following steps in order to process each data file:

- detecting and classifying faults
- specifying expected protection system operation,
- extracting actual operation of the protection system,
- comparing expected and actual protection system operation,
- assessing protection system performance based on the results of the comparison.

It has been noticed that, potentially it may be difficult to select generalized logic settings of such a system. Namely, as in every rule-based system, certain thresholds (i.e., the knowledge) have to be specified in the rules. Fine tuning the thresholds in the rules may be needed as the system conditions dramatically change.

Also, the conventional rule-based analysis systems may be too slow to be applied in real-time environments since under certain conditions they require time-consuming process of rule- and knowledge-base search.

Due to the mentioned potential limitations of the rule-based system solution, a study of the neural net application to fault detection and classification was initiated [4].

Enhancements to the expert systems can be achieved by using the neural networks [5]. Figure 6 (representing an existing rule-based system) and Figure 7 (representing a combination of neural net and rule-based system) show how the two solutions differ from one another.

Event No.	Date/Time Stamp	Analyzed
event200	08/21/95 12:49:17.390	Yes
event416	07/22/95 05:04:34.912	Yes
event520	03/07/95 06:32:32.159	Yes
event551	07/14/95 12:18:46.438	Yes
event625	03/28/95 02:59:38.756	Yes
event369	12/18/95 06:35:16.747	Yes
event429	12/28/95 09:21:50.337	Yes
event207	05/07/96 04:06:43.911	Yes
event208	05/03/96 07:12:06.385	Yes
event209	05/05/96 22:05:27.314	Yes
event210	05/05/96 22:06:02.914	Yes
event206	05/21/96 04:59:28.234	Yes
event202	05/12/96 20:15:53.830	Yes
event203	05/27/96 11:11:18.840	Yes
event204	05/28/96 08:15:28.954	Yes
event205	05/20/96 07:57:28.396	Yes
event201	05/09/96 13:29:14.642	Yes

Figure 4. DFR Assistant's top level window

**Additional Event Description**

The fault is cleared by the protection system at the substation.

Primary relay operation time is 0.0957 sec.

15.7402 cycles and ends at 0.1118 sec (8.7080 cycles).

The middle 225 contacts operates at 0.1235 sec (1.130 cycles).

The last 176 contacts operates at 0.1243 sec (1.1343 cycles).

The busbar manual change after trip is reported at 0.2286 sec (1.7178 cycles).

The middle breaker manual change after trip is reported at 0.2286 sec (1.7178 cycles).

The last breaker manual change after trip is reported at 0.2286 sec (1.7178 cycles).

**Digital Fault Recorder Information**

DFR ID S.T.P.

DFR Model Progress TR162C

Sampling 5.33 (Hz)

**General Event Information**

Location 61444444444444444444

Date/Time 08/20/95 06:03:32.159

Event Size 25.3 (cycles)

**Event Classification**

Event Type phase to ground fault

Line Involved GSA-HYMAN Ckt 844

Fault Location 51.36 (miles)

**Event Data**

Phase	Fault Type	Time (sec)	Current (A)
Ra	0.2478	0.2362	0.0000
Rb	0.2478	0.2362	0.0000
Rc	0.2478	0.2362	0.0000
Y0	0.0000	0.0079	0.0000
N0	293.9000	296.4000	282.0000
N1	294.0000	295.9000	284.0000
N2	295.0000	291.4000	284.0000
N3	491.0000	484.0000	480.0000

Figure 5. DFR Assistant's analysis report view

Figure 7 shows a hybrid system that contains neural nets for disturbance detection and classification, and rule-based analysis system for evaluation of the protection system performance. A separate neural net is trained for every transmission line in the substation. An automated training can be implemented using advanced digital simulator software [6]. Trained net is, then, used for fast disturbance detection and classification. The results of this classification, which are logic type outputs, are used together with the digital contacts data (e.g., relays, communication channels, breakers, etc.) in the expert system part to assess the performance of the substation protection system.

- This system can be used in two different modes of operation:
- event processing based on a data "snapshot",
  - event processing based on a "continuous" data flow.

The first mode of operation is a conventional approach, where digital fault recorder, based on its internal triggers, records the event. The event is then transferred to the neural net expert system for automatic processing.

The second mode of operation assumes continuous data flow from digital fault recorder (or, any other data acquisition device). In this case, the neural network "triggers" the analysis based on its detection capabilities.

## B. System Wide Analysis

Other enhancements to the existing automated analysis system are currently investigated in the area of system wide analysis. A development effort is under way to implement an analysis approach where the overall power system condition after occurrence of a fault is assessed to determine if the system stability is maintained and what are the possible restoration actions that may be required.

The other effort is aimed at developing an analysis system capable of utilizing data coming to the central location not only from DFRs but also from sequence of events recorders (SERs), advanced microprocessor based relays and other digital equipment installed in the field. This approach would enable comprehensive analysis of a given event (fault) in the system providing detailed description in a very short period of time after disturbance. This would also help system dispatchers to make reliable decision regarding system restoration, and give protection engineers powerful tools for better assessing the performance and maintaining protective relay-system.

The Global Positioning System (GPS) technology is presently investigated to identify the benefits for the system-wide analysis so that future recommendation regarding the use of the GPS receivers for synchronizing data acquisition in substations can be formulated. As a result, a high accuracy fault location algorithm that can enhance the analysis of the events associated with a transmission line connecting two substations has been developed and evaluated. In addition, utilization of the synchronized samples in calculating the phase angle difference between the two ends of the transmission line has been investigated. [7]

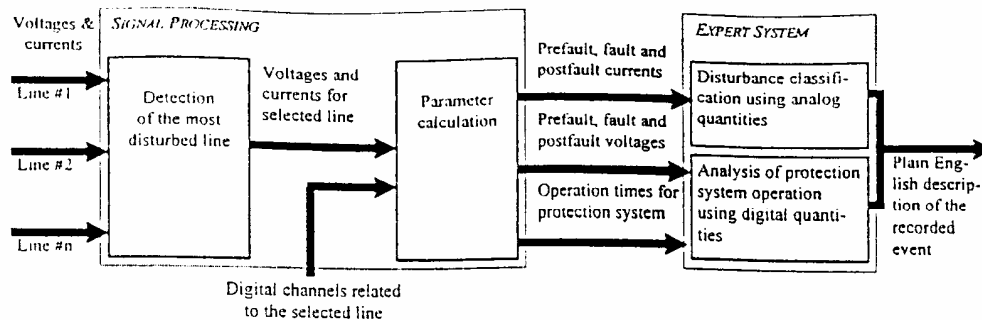


Figure 6. Data flow diagram of the rule-based analysis system

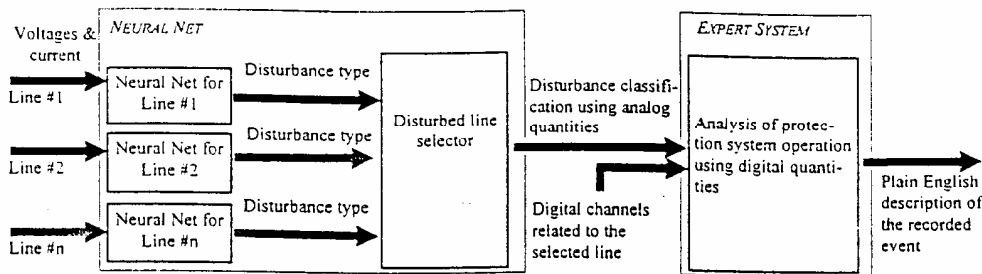


Figure 7. Combined neural net and rule-based analysis system

## VI. Conclusions

Development efforts reported in this paper indicate that:

- Automated analysis of DFR records is feasible and cost effective solutions are commercially available.
- Several system solutions for the automated analysis are possible and the final choice depends on the intended uses of the analysis results.
- Further automated analysis enhancements using neural nets are quite promising but do require adequate tools for neural net training.
- Future directions in the system wide analysis include automated correlation of the analysis results obtained from different substations as well as addition of the results obtained by performing automated analysis of the data coming from SERs, protective relays and other intelligent electronic devices (IEDs).
- System-wide synchronization of the substation data acquisition using GPS receivers shows improvements in the fault location and phase angle difference measurements and may enhance the ability of analyzing system-wide events.

## Acknowledgments

Thanks are due to HL&P and TU Electric for providing funding to TLI, Inc and TAMU respectively for field installation of the system-wide solutions reported in this paper.

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