# DIGITAL FAULT RECORDER FILE CLASSIFICATION AND ANALYSIS USING EXPERT SYSTEM AND SIGNAL PROCESSING TECHNIQUES

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## INTRODUCTION

The use of expert systems for event analysis has been investigated for the last 10 years and a number of different approaches were suggested [1,2]. These approaches are based on the use of various substation devices and systems such as Remote Terminal Units (RTUs) of Supervisory Control and Data Acquisition (SCADA) System, Sequence of Event (SOE) recorders, Digital Relays, and Digital Fault Recorders (DFRs) [3]. The events were analyzed based on alarms [4], circuit breaker and relay contacts [5], and analog current and voltage signals [6]. In most of the cases a unique implementation approach was taken regarding selection of expert system rules, programming language and computer system [7].

This paper concentrates on the use of Digital Fault Recorder (DFR) files for substation event analysis. Records captured in a substation by DFRs are quite often numerous and their classification and analysis may take a tremendous amount of time. The protection engineers responsible for explaining various power system events have identified a need to automate the classification and the analysis process and to provide system dispatchers with useful information. As a result, an expert system was built to assist engineers in this time consuming task.

This paper discusses a two year research and development effort that has resulted in an expert system prototype that has been extensively tested and evaluated. A number of power system disturbances and faults were recorded on the Houston Lighting & Power (HL&P) system. A dozen of these events were analyzed by protection engineers at HL&P and were also subjected to the expert system for automated analysis. The results from the expert system were obtained much quicker than what was possible otherwise. The expert system conveyed many of the conclusions that experts would make. The expert system also displayed the analysis steps which were very useful in making detailed analysis of the equipment operation. The expert system was also demonstrated to other HL&P personnel coming from generating stations, system maintenance and control center. These individuals have indicated that the results could be of use for their every day tasks, i.e., supplement existing SCADA information when responding to system disturbances. Further development activities were identified for making this expert system a system–wide solution that could be used by different branches within a utility company.

## APPLICATION REQUIREMENTS

Common practice in Houston Lighting & Power (HL&P) Company is to collect disturbance and fault data by digital fault recorders. This data is used for post mortem analysis. Important goals of the analysis are either to identify misoperation or to confirm correct operation of relays and breakers during faults. For this purpose, substations are equipped with a total of 23 DFRs which can communicate to a computer located in the protection engineers' offices.

One of the main problems encountered in trying to utilize DFR data is the large number of disturbances and fault records captured. In order to analyze this data, an efficient way of classifying records is needed. A manual search to identify fault records of interest is time consuming. In particular, it is time consuming to distinguish between fault transients and other transient events that may trigger the recorder but do not actually represent a fault event.

Therefore, the main problem to be resolved is to automate both event classification and analysis of fault events. Fault events are of primary concern while switching events are of secondary concern. As a result, an expert system was specified as a possible solution to this problem.

The Expert System developed here automates analysis and classification of disturbance events by using the approach and the analysis method similar to the ones used by the expert. This section describes the experts' approach to problem solution, techniques used in the event and the protection system analyses, and data requirements for the analysis.

**Expert's Approach**

Guidelines for the knowledge inference process are deduced by analyzing the experts' approach to the problem solution. It is important to analyze both the expert's knowledge sources and their analysis procedure.

Expert's approach to the solution of the fault detection and classification problem involves experience, knowledge about the network topology, network parameters, generation and load allocation, information on the contact status, and DFR data from several substations in the system.

Experts have experience regarding the fault signal behavior. Characteristic system behavior can easily be identified. Exceptions are harder to specify and are not well documented.

Experts' knowledge about network topology, network parameters, and generation and load allocation allows for a better picture of power system conditions in case of a fault. For example, experts can have an idea about load flows prior to a short circuit which is not known without certain computations. Information on the contact status gives experts an insight into the protection system reaction to a power system event. In the case of correct and accurate operation, the protection system should activate breakers that would only disconnect the faulted line(s).

DFR data obtained from several substations provides system-wide, status contacts and analog signal waveforms. Comparison of DFR data obtained from different substations allows for three advantages. First, it allows for an accurate and complete picture of the relay and breaker action. Secondly, it provides a system-wide picture of voltage and current disturbances. Events with the same time tags allow for a comparison of signal disturbance amplitudes and relative phases. Thirdly, this information is redundant and, therefore, allows for detection of equipment misoperation and failure.

Generally, DFR data may be incomplete for two reasons. Very often, DFRs are not installed at each substation. Also, DFRs usually do not cover all analog signal waveforms and contacts at one substation because the number of available DFR channels is not always sufficient. Experts try to fill in gaps caused by this incompleteness.

Some aspects of the experts' approach are embodied in the expert system design reported in this paper. An expert system that performs the fault diagnosis using data obtained at a single substation was the design task of this project. DFR event data recorded at a substation is the only information source.

### Event Analysis

Knowledge necessary for event analysis was acquired by interviewing experts, namely protective relay engineers, and by using an empirical approach described later.

The event analysis provides hypotheses on the character and the sequence of events recorded in the analyzed event file.

The majority of the events that trigger DFRs are just switching or lightning events and not faults. Filtering fault events from the whole set of recorded disturbance events takes a lot of work and time due to the fact that almost 95% of the recorded events are not fault events. Furthermore, the number of recorded events may be huge and data recorded at each substation is overwhelming. The general event and protection system operation analysis procedure, with some details, is described below.

- Fault inception instant is detected by looking for the initial change in signal waveforms. (Trigger instant is not always the same as the fault inception instant.)
- Voltage waveforms are checked for a change in the fundamental frequency harmonic amplitude. A voltage decrease indicates the possible faulted phase(s).
- Only current channels of the phase(s) that have experienced a significant voltage decrease are checked next. The currents that have experienced a maximum amplitude increase indicates the probable fault direction.
- 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 (e.g., temporary, permanent) and the behavior of the protection system (e.g., fault clearing, reclosing).
- Contacts' state is checked for a change. A status change is an indication that the protection system has detected a fault.
- If both the protection system operation and the "no fault" disturbance are detected, 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 the protection system failure.

The following simple "rules of thumb" describe waveform patterns that characterize disturbances:

- Switching surges and other types of transient disturbances produce short (typically up to half a cycle) waveform distortion. This distortion is not captured in the filtered signal waveform.
- Faulted phase gives a decrease in voltage and an increase in current.
- Increase in current is maximum for the line in the faulted direction.

- Ground faults give an increase in zero sequence currents and voltages.

- If a relay contact has changed its status then there is a fault in the power system or a misoperation in the relay system.

- Status of an open breaker may be confirmed by the current amplitude being close to zero.

- Breaker operation failure shows as a no breaker status change for a change in the relay contact status.

To provide the event sequence analysis, recorded data is analyzed for all significant changes in analog parameter data. The following events are identified:

- 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.

Typical examples of these events are given in Figures 1–7.

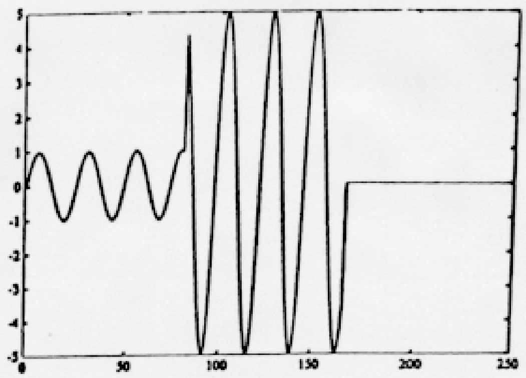


Fig. 1. Fault Clearance at the Monitored Substation

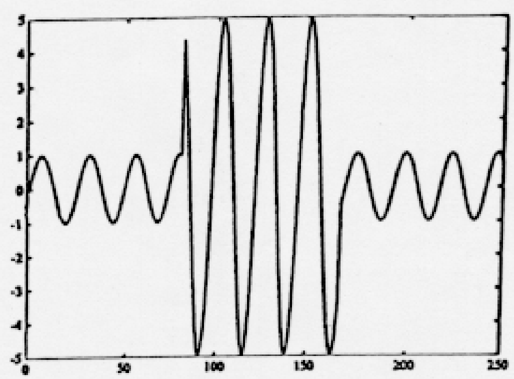


Fig. 2. Fault Clearance at Some Other Substation

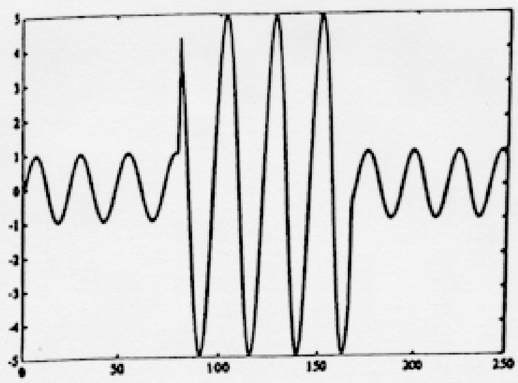


Fig. 3. Self Clearance

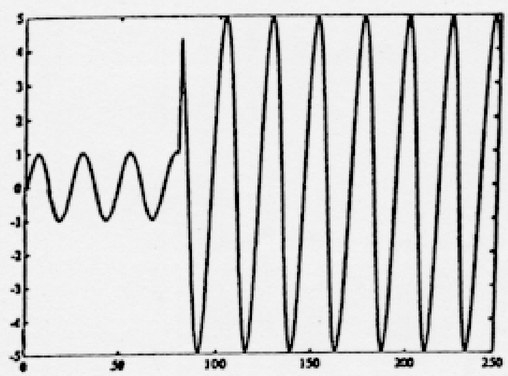


Fig. 4. No Clearance of a Fault

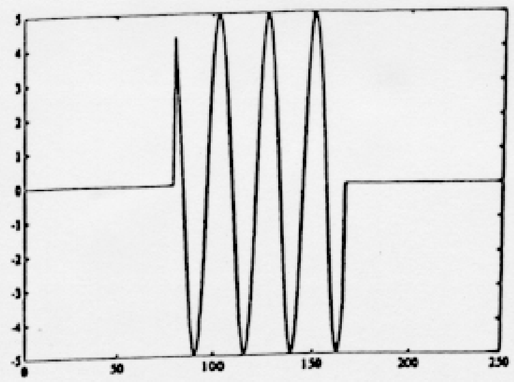


Fig. 5. Reclosure Failure

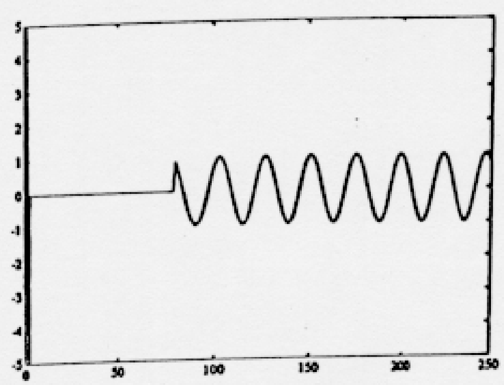


Fig. 6. Reclosure Success

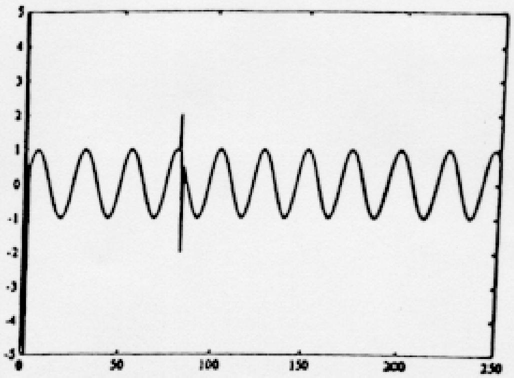


Fig. 7. "No Fault" Disturbance

### Data Requirements

For performing both the event and the protection system operation analysis, substation and DFR configuration data is necessary. Some of the configuration information can be found in the DFR configuration files, but nevertheless, some of the necessary information is missing. (Configuration information will be discussed in more detail in the next chapter.) Missing configuration information is provided by experts.

Also, knowledge about the breaker and relay operation schemes is essential for the protection system operation analysis. These schemes are substation specific.

### Protection System Operation Analysis

Knowledge required for the protection system operation analysis was acquired mainly through interviews with experts.

Protection system operation analysis provides hypotheses on the correctness of breaker and relay operation.

All protection equipment status data includes samples of predisturbance, disturbance and postdisturbance contact positions. Contacts of protection equipment are either normally closed or normally opened. DFRs record their position in time. Any change in position is used for monitoring the operation of the protection system and deriving useful conclusions in the fault diagnosis process.

The possibility of device error requires constant monitoring of relay and breaker operation. There are two types of errors: device misoperation and failure. The former type includes erroneous device operations in the case of a disturbance that is not a fault. The latter includes the operation failures in case of a fault.

Three types of contact status data provided with DFR event files can be distinguished as follows:

- Breaker contact status data.
- Relay contact status data.
- Communication contact status data.

*Breaker contact status* data provides information about the breaker being open or closed. "One and a half breaker scheme" is the breaker scheme used in this development. This scheme uses two breakers to disconnect a faulted line. One of the two breakers is used by both relays disconnecting two different lines. For each relay operation, two associated breakers need to operate to disconnect the faulted line.

*Relay contact status* data includes primary and backup relay operation signals sent from the relays to the associated breakers.

*Communication contact status* data includes the history of transmitter and receiver blocking signals. Substation STP protection system includes both TC (on/off pilot blocking signal) and TCF (breaker failure direct transfer trip) transmitter and receiver contacts. TC contacts are instrumental in performing the "directional comparison blocking scheme." TCF contacts realize a "breaker backup security system." Both schemes are described below.

*The directional comparison blocking scheme* is used by the protection system to allow for a faster and more reliable protection. It is a scheme that is used with *primary relays* at the substation STP. This scheme tries to localize and disconnect the faulted section from the unaffected part of the power system. It uses TC communication signals initiated by relays to avoid disconnecting unfaulted sections. Two relays, one on each side of the line, communicate to decide whether the existing fault is somewhere in between. If one believes that the fault is not in the guarded section, it sends a blocking signal to the other. The relay that receives a blocking signal is blocked from tripping the breaker regardless to what its own decision may be.

Two relay modules cooperate to make this scheme function. One module acts as an overreaching directional relay. The other module acts as an overreaching non directional relay.

The relay is blocked from tripping in two cases. The first case is when it receives a blocking signal from the relay on the other end of the line. The second case is when the non directional module sees a fault and the directional does not. In the latter case, this relay sends a blocking signal to the relay on the other end of the line because it believes that the fault is out of their guarded section.

The relay trips the breaker when there is no blocking signal and when the directional module sees a fault. These two conditions assure, with a high level of probability, that the faulted section is the one guarded by this relay.

The breaker *backup security system* at this substation functions as follows. A separate relay unit checks the current flow after the breaker has been tripped. If the breaker does not open on time the TCF transmitter signal is set. This signal trips all the local breakers and the breaker on the other end of the line. In this way the fault is still isolated.

The non pilot time zone *backup relays* work in a "three zone scheme." This scheme is used with *backup relays*. The second and the third zone *time delays* allow the primary relay to clear the fault. Backup relays should operate when the primary relays do not clear the fault on time. For a full error detection, backup relay function needs to be checked for all three time zones. Also, backup relays at this substation include the instantaneous units that trip for close high current faults before primary relays do.

Specifics of these schemes are used by the system for detection of protection system failure and misoperation. This detection is implemented in the Expert System diagnosis block. The operation of each unit is analyzed and any errors are indicated by this block.

## IMPLEMENTATION APPROACH

Expert system implementation block diagram is given in Figure 8. It consists of data conversion, substation description interface, signal analysis, event diagnosis, and result presentation blocks.

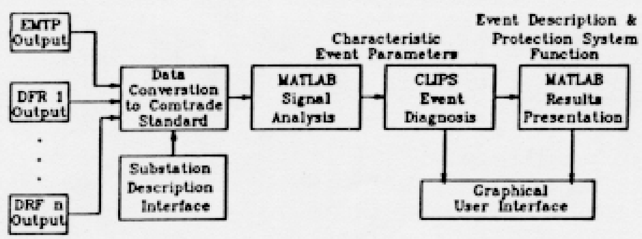


Fig. 8. Expert System Block Diagram

Data conversion block translates format of data generated by EMTP [8] and different DFRs into a format suitable for analyzing by MATLAB [9]. Additional substation description interface is developed to make up for insufficient EMTP/DFRs configuration data. A MATLAB program analyzes row data to provide parameters required for the diagnostic process. CLIPS, an expert system shell [10], takes data from MATLAB to make final conclusions on the fault detection and diagnosis.

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, and breaker, relay and communication parameters for the transmission line that demonstrates the largest current disturbance. This line is extracted from the set of substation transmission lines by MATLAB. MATLAB also distinguishes the three characteristic time intervals of the event. These time intervals are the predisturbance, disturbance, and post disturbance. It calculates the voltage and current RMS values for the three time intervals as the analog signal parameters. MATLAB identifies breaker and relay change of status times as protection system parameters. It also analyzes the communication signal operation intervals to state 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, and all together these information include complete step by step reasoning process performed by CLIPS shell, as well as plot of voltage and current waveforms for disturbed transmission line, and status and communication signals.

### Standard Data Format

There are as many DFR record formats as there are DFR manufactures. Even DFRs produced by a single manufacturer may have their data recording formats changed from one DFR type to another. This represents serious problem to develop automated (computer aided) deciphering mechanisms to acquire the desired data and to put it in suitable format. This has generated the need for a standard format for the exchange of data for use with various devices to enhance and automate the analysis, testing, evaluation, and simulation of the power system and related protection schemes during fault and disturbance conditions. Such a standard, called IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems has recently been approved [11]. It defines sources of transient data, data exchange medium, data exchange sampling rates, files for data exchange, and organization of transient data.

There are two main problems that are related to the expert system input data and they are discussed below.

The problem of incompatible DFRs formats encountered during the development of expert system is solved by creating software conversion interfaces for each DFR, which convert the data format specific to a given device into a COMTRADE standard format. In that way, it does not matter what the actual DFR output format is as long there exists conversion software to COMTRADE. This feature is valuable to the utility companies that have DFRs from different manufacturers. For the expert system reported in this paper there are two DFR interfaces developed so far, one for the Rochester and the other for Hathaway DFRs.

The other problem is that configuration file in COMTRADE standard does not contain all necessary information needed for reasoning process of the expert system. The fault detection and classification function of the system can be made very general and be applied to a wide spectrum of substations if complete DFR configuration data is available. It was not possible to develop sufficiently general representation of the network topology and extract information on the contact status based solely on the configuration file. For example, the names used for DFR channels are not in a standard format. This makes the automatic interpretation of channel names a task that is too involved. Digital channel names, too, can not be interpreted in a way that provides any significant information and are deemed useless. Also, contact data records are very much specific to protection scheme types used at a given substation. To overcome this problem, the substation description interface is developed. It is menu driven and allows operator to enter necessary information for describing the network topology and relative position of relays, and related breakers and circuits.

### Expert System Rules

Experts' approach and analysis techniques are implemented in the form of CLIPS rules after determining thresholds for characteristic waveform patterns. The list of rules and their description is given in Table I. Calculation of thresholds that classify faults is described below.

Fault classification is based on analog parameter thresholds for the characteristic waveform patterns. These are determined in the testing process.

Test cases consist of EMTP and DFR cases. The summary of test cases is given in Table II. Test cases shown in the first five rows of this table were simulated with EMTP. The first three runs represent cases produced by simulating faults on the HL&P system given in Figure 9. The next 2 rows are cases obtained by simulating faults on an artificial system shown in Figure 10. The last four cases are "real–data" DFR case. KING-NBELT and KING-GRBAY are cases recorded in the HL&P system (Figure 9). Brevard-Cocoa Beach and Brevard-EAU DE GALLIE are cases registered on the FPL system shown in Figure 11. Test cases analysis results in the thresholds for the characteristic relations given in Table III. An example of a CLIPS rule that implements these relations is given in Figure 12. This rule classifies the A to B to ground faults.

Table I. List of Rules Based on Voltage & Current Waveforms

| | Rule Name | Rule Description |
|---|---|---|
| 1. | is_fault | fault detection |
| 2. | is_ground_fault | determines ground faults |
| 3. | no_ground_fault | determines line faults |
| 4. | phase_A_ground_fault | determines phase A to ground fault |
| 5. | phase_B_ground_fault | determines phase B to ground fault |
| 6. | phase_C_ground_fault | determines phase C to ground fault |
| 7. | phase_AB_fault | determines phase A to B line fault |
| 8. | phase_BC_line_fault | determines phase B to C line fault |
| 9. | Phase_CA_line_fault | determines phase C to A line fault |
| 10. | phase_ABC_fault | determines three phase faults |
| 11. | breaker_open_predist | determines whether breakers were open before disturbance |
| 12. | breaker_open_dist | determines whether the breaker was open at all during the disturbance |
| 13. | breaker_open_postdist | determines whether the breaker was open after the disturbance |
| 14. | reclosure_attempt | determines reclosure attempt |
| 15. | reclosure_failure | determines reclosure failure |
| 16 | fault_clearance_here | determines whether the fault was cleared at the breaking substation |
| 17. | fault_clearance_other_self | determines whether the fault cleared elsewhere |
| 18. | not_clearance | determines that the fault was not cleared |
| 19. | protection_failure | determines a failure in the protection system operation |
| 20. | reclosure_success | determines that reclosure attempt was successful |
| 21. | protection_misop | determines that the protection system operated when it should not have |
| 22. | protection_failure_reclose | determines that the reclosure failure was not successful |
| 23. | bus_open_all | bus breaker is open al the time |
| 24. | middle_open_all | middle breaker is open all the time |
| 25. | bus_open | bus breaker opening instant |
| 26. | bus_close | bus breaker closing instant |
| 27. | middle_open | middle breaker opening instant |
| 28. | middle_close | middle breaker closing instant |
| 29. | primary_operation | primary relay operation interval |
| 30. | backup_operation | backup relay operation interval |
| 31. | breaker_delay | breaker delay after the trip |
| 32. | bus_failure | bus breaker fails to operate |
| 33. | middle_failure | middle breaker fails to operate |
| 34. | relay_misoperation | relay tripped when it should not have |
| 35. | primary_failure | primary relay failed to trip |
| 36. | backup_failure | backup relay failed to trip |
| 37. | primary_misoperation | primary relay operated when it should not have |

### Table II. Summary of Test Cases

| Fault Location | AG | AB | ABG | 3PH | 3G |
|---|---|---|---|---|---|
| NBELT | x | x | x | x | x |
| WHART | x | x | x | x | x |
| WHART HZ | x | | | | |
| M12, B1 | x | x | x | x | x |
| M12, B8 | x | x | x | x | x |
| KING-NBELT | x | | | | |
| KING-CEDBAY | x | | | | |
| B-E | x | | | | |
| B-C | x | | | | |

- **Fault Types**

- AG: Phase A to ground fault
- AB: Phase A to phase B fault
- ABG: Phase A to phase B to ground fault
- 3PH: Three phase fault
- 3G: Three Phase to ground fault
- NBELT: The fault at NBELT, measured at KING
- WHART: The fault at WHART, measured at KING
- WHART HZ: High impedance fault at WHART, measured at KING
- M12, B1: The fault at the middle of Line 1-2, measured at Bus 1
- M23, B8: The fault at the middle of Line 1-2, measured at Bus 8
- KING-NBELT: The fault to NBELT, recorded at KING on the line to NBELT
- KING-CEDBAY: The fault to NBELT, recorded at KING on the line to CEDAR BAYOU
- B-E: The fault to COCOA BEACH, recorded at BREVARD on the line to EAU de GALLIE
- B-C: The fault to COCOA BEACH,recorded at BREVARD on the line to COCOA BEACH

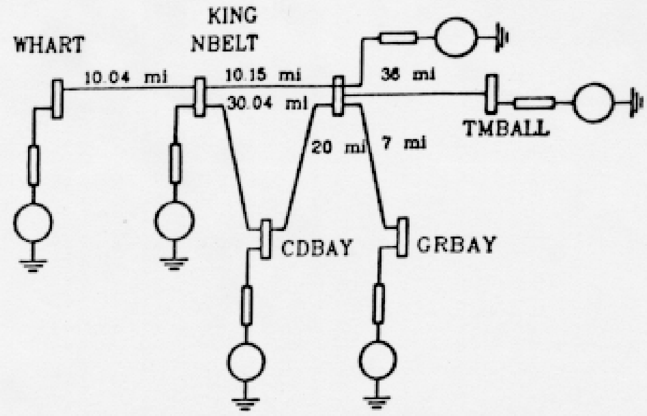


Fig. 9. One Line Diagram of the Reduced HL&P System

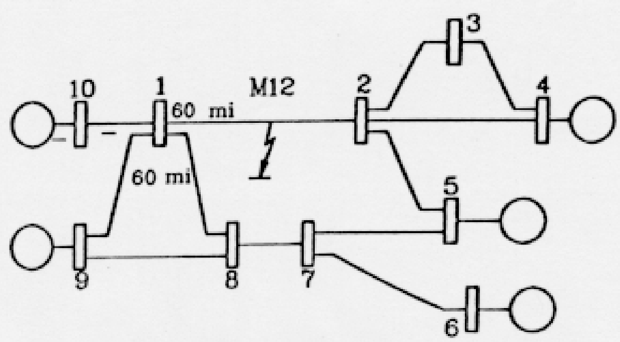


Fig. 10. Bus Test System

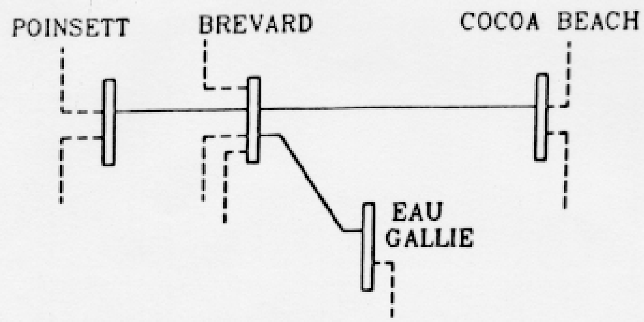


Fig. 11. Part of FPL Transmission System

**Table III. Adopted Threshold Values**

| Relations [%] | AB | AB | ABG | 3PH & 3G |
|---|---|---|---|---|
| $min(I_0/I_a)$ | 6 | | 6 | |
| $max(I_0/I_a)$ | | 6 | | 6 |
| $min(I_a/I_p)$ | 130 | 150 | 130 | 150 |
| $min(I_b/I_p)$ | | 150 | 130 | 150 |
| $min(I_c/I_p$ | | | | 150 |
| $max(I_b/I_a)$ | 50 | | | |
| $max(I_c/I_a$ | 50 | 20 | 70 | |
| $max((I_a - I_b)/I_a)$ | | 15 | 20 | |
| $max(I_0 - I_a)/I_a$ | 96 | | | |
| $min(V_0/V_n)$ | 4 | | 10 | |
| $max(V_0/V_n)$ | | 1 | | 2 |
| $max(V_a/V_n)$ | 93 | 85 | 80 | 85 |
| $max(V_b/V_n)$ | | 85 | 80 | 85 |
| $max(V_c/V_n)$ | | | | 85 |
| $min(V_b/V_n)$ | 95 | | | |
| $min(V_c/V_n)$ | 95 | 96 | 96 | |
| $max((V_a - V_b)/V_n)$ | | 5 | 5 | 5 |
| $max((V_b - V_c)/V_n)$ | 5 | | | 5 |
| $min((V_c - V_a)/V_n)$ | | 15 | 20 | |
| $max((V_{ab} - V_{ca})/V_{ln})$ | 10 | | | |
| $max((V_{bc} - V_{ab})/V_{ln})$ | | | | 5 |
| $max((V_{bc} - V_{ca})/V_{ln})$ | | 5 | 5 | 5 |
| $max((V_{bc} - V_{ln})/V_{ln})$ | 1 | | | |
| $min((V_{ab} - V_{bc})/V_{ln})$ | | 15 | 15 | |

```
(defrule phase_AB_ground_fault
        (declare (salience 40))
        (ground fault)

        (ip ?I0p ?Iap ?Ibp ?Icp)
        (I ?I0 ?Ia ?Ib ?Ic)
        (Vp ?Vap ?Vbp ?Vcp ?V0p)
        (V ?Va ?Vb ?Vc ?V0)
        (Vlp ?Vabp ?Vbcp ?Vcap)
        (Vl ?Vab ?Vbc ?Vca)

        (test (> ?Ia (*1.3 ?Iap)))
        (test (> ?Ib (*1.3 ?Ibp)))
        (test (< ?Ic (*.7 ?Ia)))
        (test (< (abs (-?Ia ?Ib))   (*.2 ?Ia)))
        (test (> ?V0 (*40 ?V0p))) ;Vap<— V0p; .1<— 40; ;'<'<—'>;
        (test (< ?Va(*.8 ?Vap)))
        (test (< ?Vb(*.8 ?Vbp)))
        (test (< (abs(-?Va ?Vb))  (*.25 ?Vap))); ;.05<—.25
        (test (> (- ?Vc ?Vb) (*.2 ?Vcp)))     ;'<'<—'>'; .15<—.2
        (test (< (abs (-?Vca ?Vbc)) (*.2 ?Vbcp))) ;.05<—.2
        (test (> (- ?Vbc ?Vab) (*.2 ?Vabp)))

⇒

        (assert (fault phase_AB ground))
        (fprintout t crlf "The disturbance is a line A to line B to ground
                                                            Fault." crlf))
```

Fig. 12. Example of a CLIPS Rule

## PERFORMANCE DEMONSTRATION

To demonstrate the ES performance, a description of the experts' approach, the ES reasoning process, ES graphical and textual output for the two "real world" DFR events are given below. Both events were recorded at the STP substation. A one-line diagram of the STP substation is given in Figure 13. The first event is a two phase to ground fault cleared at another substation. The second event is a 'no fault' disturbance caused by switching.

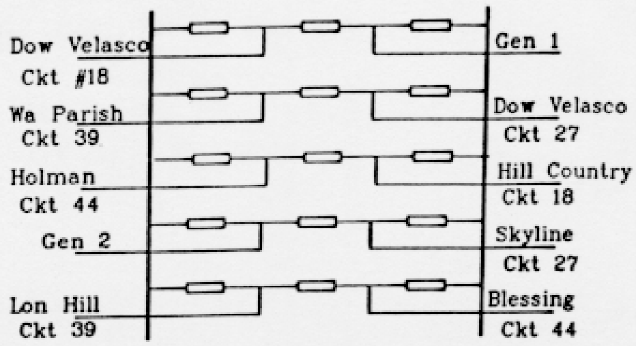


Fig. 13. A One-Line Diagram for STP Substation

For both events, relay engineers first need to analyze 48 analog channels before determining the channels with the most abrupt signal disturbances. These signals carry most of the information that describe the event and provide the fault detection. After analyzing the event, they analyze the corresponding contact status signals to check the protection system operation. This results in a complete diagnosis.

For the first event, engineers would notice that phase C and A currents of circuit 39 to W. A. Parish show the greatest changes. Comparing these changes to the change in phase B current and by looking at the zero sequence current, they would conclude that the event was a phase C to phase A to ground fault (Figure 14).

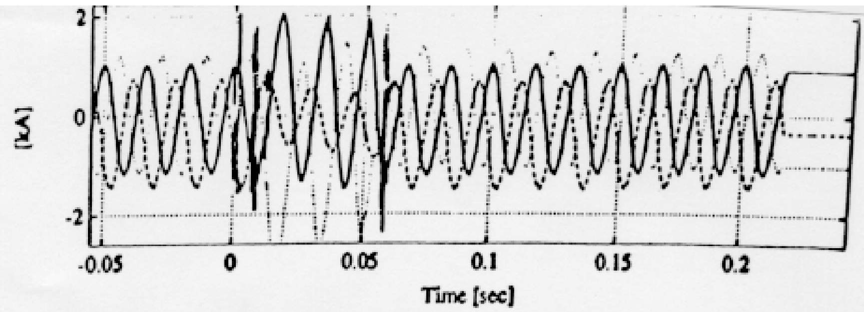


Fig. 14. Display of Phase Currents

The current nominal value observed after the disturbance period indicates that the fault was cleared at another substation. Protection system signals show that relays did not trip and that the breakers did not operate during the event (Figure 15).

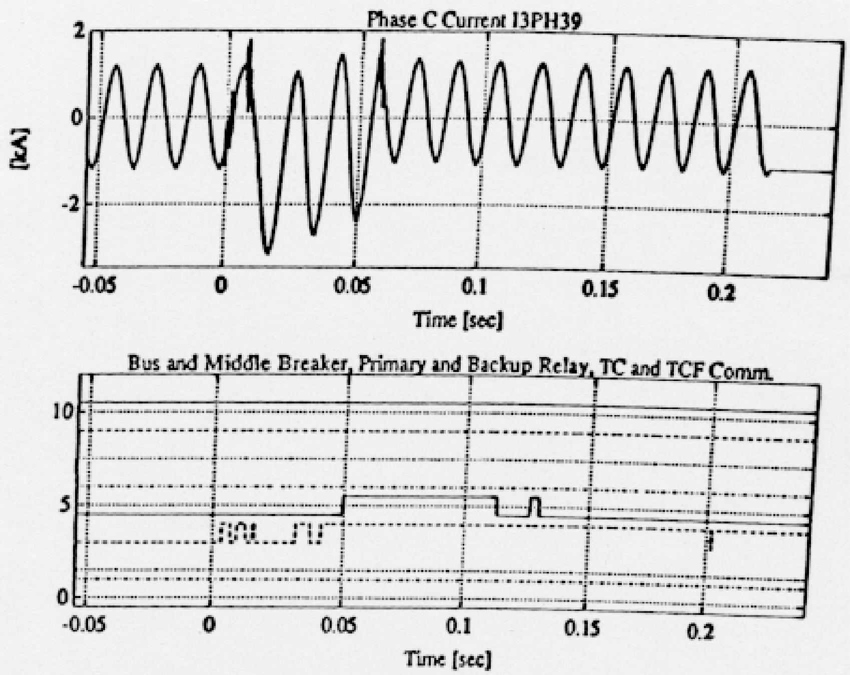


Fig. 15. Behavior of the Fault Current and Related Contacts

Figure 16 shows the event description which would coincide with the experts' opinion.

****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

Fig. 16. Event Description Given by the Expert System

For the second event, engineers would notice that currents of circuit 18 to Hill Country show the greatest changes. But, they would notice that there is no significant change in the fundamental frequency components of the signal (Figure 17).

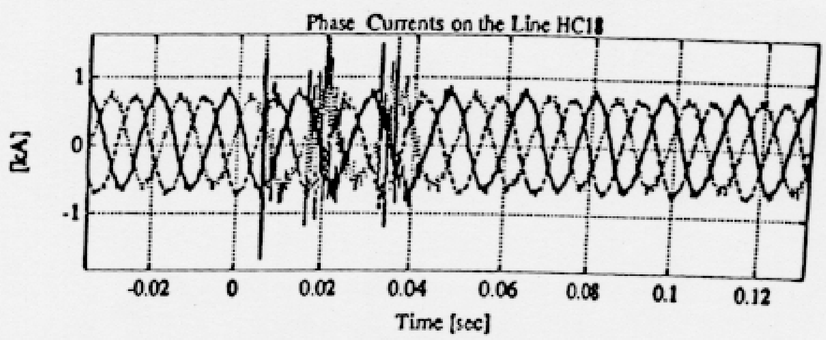


Fig. 17. Display of Phase Currents

By comparing the disturbance interval and the breaker operation interval, they would notice that the disturbance was induced by the breaker opening (Figure 18).

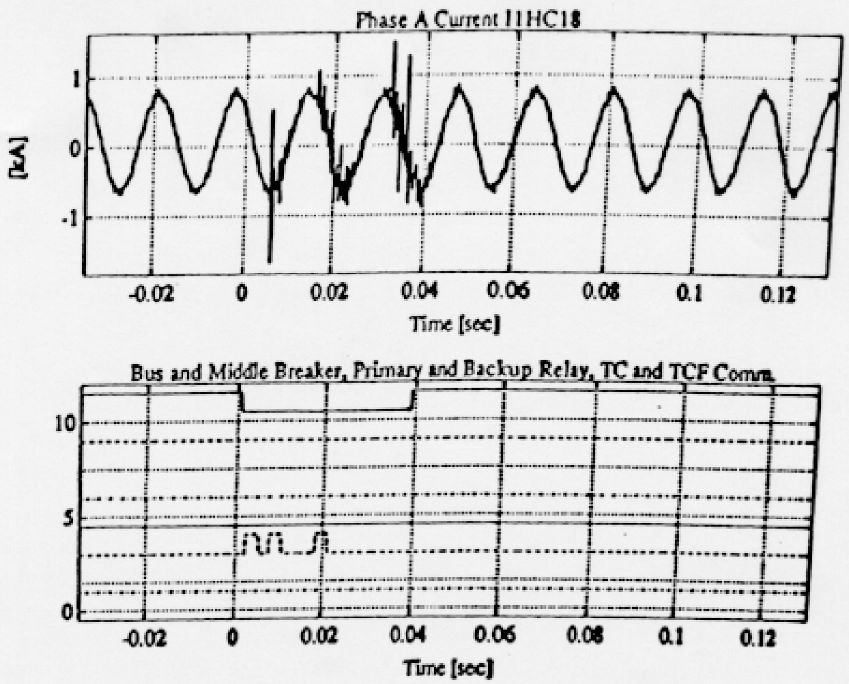


Fig. 18. Behavior of the Current Disturbance and the Related Contacts

Figure 19 shows the ES event description which would coincide with the expert's opinion.

```
****Welcome to the brain of the Fault Detection and****

****EVENT DESCRIPTION USING ANALOG DATA****

HC18 is the circuit with largest current disturbance.

The disturbance is not a fault.

****PROTECTION SYSTEM OPERATION ANALYSIS****

The bus breaker closes at 0.001 seconds.
It opens at 0.039 seconds

Protection system behaved correctly.
It did not operate for a switching surge
induced by breaker opening on this line

Thank you
```

Fig. 19. Event Description Given by the Expert System

Expert System's diagnosis is followed by a display of significant event signals. This display aids operators in quickly verifying expert system performance.

## CONCLUSIONS

Based on the developments reported in this paper, the following can be concluded:

- Fault detection and diagnosis are time consuming activities that require expertise specific to given system operation practices and equipment characteristics.
- Expert system technology can be utilized to automate fault detection and diagnosis process
- Major benefits of the expert system application to this problem are savings in processing time and improvements in the overall analysis.

## ACKNOWLEDGEMENTS

The activities reported in this paper were funded by Houston Lighting and Power (HL&P) Company of Houston, Texas, U. S. A. Special thanks are due to HL&P's protection engineers Messrs. C. W. Fromen and D. R. Sevcik for sharing their expertise incorporated in the expert system rules.

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