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AN EXPERT SYSTEM FOR TRANSMISSION SUBSTATION EVENT ANALYSIS

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Abstract– Digital fault recorders (DFRs) are used in substations to capture recordings of various disturbances and fault events. Protection engineers use these recordings to identify reasons for particular operation of protection relays and circuit breakers. In performing this task protection engineers use their expertise related to specific power system conditions, equipment and operations. This paper describes implementation of an expert system which performs fault detection and diagnosis automatically and can aid operators in their task of analyzing disturbances and fault events.

Keywords: Expert System, Fault Detection, Fault Diagnosis, CLIPS, Digital Fault Recorders

INTRODUCTION

Automated analysis of circuit breaker and protective relay operation has been a focus of research and development activities since 1969 [1]. Application of artificial intelligence (AI) techniques to this problem has been studied since the late 70s and during early 80s [2,3]. As a result, expert system technology has been recognized as a promising AI approach [4-6].

Expert system application to fault analysis was studied for several years and number of system implementations were developed and tested [7]. As a result, several problem definitions and implementation approaches related to this application have been identified [8]. The main differences between various designs were in the expert system techniques selected and data acquisition equipment utilized. Most of the developments introduced so far relied on the rule based techniques using Supervisory Control and Data Acquisition (SCADA) equipment as a source of relevant field data. These systems are typically limited to breaker and switch status only.

This paper is somewhat unique since the source of system data are digital fault recorder (DFR) files. This approach has been suggested in some other recent references but the implementation approaches selected were quite different from the one given in this paper [9,10]. In this paper, signal processing techniques are used to process analog waveforms in order to determine signal parameters. These parameters are then used, with information on relay communication and circuit breaker contacts, to analyze a given event. This approach offers major improvements in the event analysis since protective relay and circuit breaker contact transition are correlated to the changes in corresponding analog signals. In this way, the short-time element is preserved due to the fact that the time sequence relation between analog signal changes and contact transitions is maintained and utilized in building the expert system rules. Also, contact data is verified by correlating its status to the related changes in analog signals.

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The expertise incorporated in the expert system rules is obtained by two means. One source of expertise were protection engineers from Houston Lighting & Power Company who were interviewed on several occasions. The other source of expertise came from simulation experiments performed using Electromagnetic Transient Program (EMTP) [11]. Several sections of different power systems were modeled and various fault events were simulated. Analysis of fault waveforms provided better understanding of the rules needed to detect various events and to diagnose faults.

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 in 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 then 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 also 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.

The first part of the paper gives a description of the detection and diagnosis problem as viewed in the context of Houston Lighting & Power substation equipment designs and operational practices. The expert system design approach is outlined next. Implementation details are provided in the following section. Results of expert system validation and testing are presented at the end.

PROBLEM DESCRIPTION

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. Manual search to identify fault records of interest is time consuming. In particular, it is time consuming to distinguish between fault transients and

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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 following two steps were identified as the main focus of the expert system design:

- Fault Detection
- Fault Diagnosis

Fault detection is a step that includes several checks used to identify a fault and determine the deviation. Therefore, fault detection classifies a fault event and characterizes the final outcome of protection system operation associated with this fault. The following is the description of a general procedure for the fault detection followed 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 phase(s).
- Current channels of the phase(s) that experienced a significant voltage decrease are checked next. The current that experienced the greatest amplitude increase indicates the probable 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).
- 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 does not indicate the presence of a fault then 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.

To illustrate some of the reasoning, a brief description of the relationship between the analog quantities in the case of a "no fault" versus a fault disturbance is given.

The system is considered either having a "no fault" disturbance or being in a steady state if all of the following relation statements are true for a transmission system (see Table I for definitions):

- Fundamental frequency currents (FFCs) are symmetric. Therefore, the zero sequence current is close to zero: $I_o \approx 0$.
- FFC amplitudes, before and after an event inception, do not show significant changes in any short time interval: $I_{uf} \approx I_p$.
- Fundamental frequency phase voltages are symmetric, therefore, the zero sequence voltage is close to zero. $V_o \approx 0$.
- Fundamental frequency phase voltage amplitudes, before and after an event inception, have approximately nominal values: $V_{uf} \approx V_n$.

In the case of a fault, the relation between voltages and currents is shown in Table I. This table summarizes relations for various types of faults. Therefore, these relations are used, not only to detect the fault, but also to classify the fault type.

Fault diagnosis is related to analysis of the protection system operation.

Protection equipment status data includes predisturbance and disturbance contact positions. Contacts of protection equipment are either normally closed or normally opened. Any change in position during a disturbance event is recorded. This information is used for monitoring the operation of the protection system and deriving useful conclusions in the fault diagnosis process.

Three types of contact status data relevant for fault diagnosis are:

- Breaker Contact Status Data

Table I. Relation Among Faulted Signals

Event Type	0 Seq. Current	Faulted Current	Unfaulted Current	0 Seq. Voltage	Faulted Voltage	Unfaulted Voltage	Line Voltage
DSS	$I_0 \approx 0$		$I_{uf} \approx I_p$	$V_0 \approx 0$		$V_{uf} \approx V_n$	
SLGF	$I_0 > 0$	$I_f > I_p$	$I_{uf} < I_f$	$V_0 > 0$	$V_f < V_n$	$V_{uf} \approx V_n$ $V_{uf_1} \approx V_{uf_2}$	$V_{lf_1} \approx V_{lf_2}$
TwPF	$I_0 \approx 0$	$I_f > I_p$ $I_{f_1} \approx I_{f_2}$	$I_{uf} < I_f$	$V_0 \approx 0$	$V_f < V_n$ $V_{f_1} \approx V_{f_2}$	$V_{uf} > V_f$	$V_{lf} < V_{luf}$ $V_{luf_1} \approx V_{luf_2}$
TwPGF	$I_0 > 0$	$I_f > I_p$ $I_{f_1} \approx I_{f_2}$	$I_{uf} < I_f$	$V_0 > 0$	$V_f < V_n$ $V_{f_1} \approx V_{f_2}$	$V_{uf} > V_f$	$V_{lf} < V_{luf}$ $V_{luf_1} \approx V_{luf_2}$
TPF	$I_0 \approx 0$	$I_f > I_p$		$V_0 \approx 0$	$V_f < V_n$ $V_{f_1} \approx V_{f_2}$		$V_{lf_1} \approx V_{lf_2}$
TPGF	$I_0 \approx 0$	$I_f > I_p$		$V_0 \approx 0$	$V_f < V_n$ $V_{f_1} \approx V_{f_2}$		$V_{lf_2} \approx V_{lf_2}$

- I_p Prefault Current
- I_0 Zero Sequence Current
- I_f Faulted Line Current
- I_{uf} Unfaulted Line Current
- V_n Nominal Phase Voltage V_{L-N}
- V_f Faulted Phase Voltage V_{L-N}
- V_{uf} Unfaulted Phase Voltage
- V_{lf} Faulted Line Voltage V_{L-L}
- V_{luf} Unfaulted Line Voltage
- DSS: Prefault Steady State
- SLGF: Single Line to Ground Fault
- TwPF: Two Phase Fault
- TwPGF: Two Phase to Ground Fault
- TPF: Three Phase Fault
- TPGF: Three Phase to Ground Fault

- Relay Contact Status Data (primary and backup relay operation signals sent to the associated breakers)
- Communication Contact Status Data (pilot relaying transmit and receive, breaker failure direct transit trip)

FORMULATION OF EXPERT SYSTEM RULES

As described in the previous section, rules are developed to identify faults, analyze them based on analog signal changes, and analyze the protection system behavior using contact status data.

Figure 1 presents a summary of rules for identifying and analyzing faults. Analog signal parameters are used to determine the hypotheses given in the circles, and to provide the fault classification.

In order to define these rules, behavior of analog signals has to be well understood, certain parameters that characterize this behavior have to be specified and threshold values for the parameters have to be determined through experimental procedures using DFR records and EMTP simulations.

Table I shows the parameters selected. This table consists of voltage and current patterns that describe *fault type*. In case that the given patterns are not satisfied, the event is *not a fault*. Figure 1 shows that there exist additional analog parameter patterns to more completely describe an event. The reasoning process implemented by rules given in Figure 1 is summarized as follows.

First, if the event is a fault, its type is determined. Second, breaker action analysis is performed to determine breaker behavior in the course of the event and consequently to provide a more complete event description. Fault type and breaker action analysis provide information to conclude about fault type, fault clearance, reclosure, and protection system operation. Also, further investigation of analog waveforms can tell whether the fault was cleared at another substation. Analysis of the breaker actions determines whether there was a fault clearance.

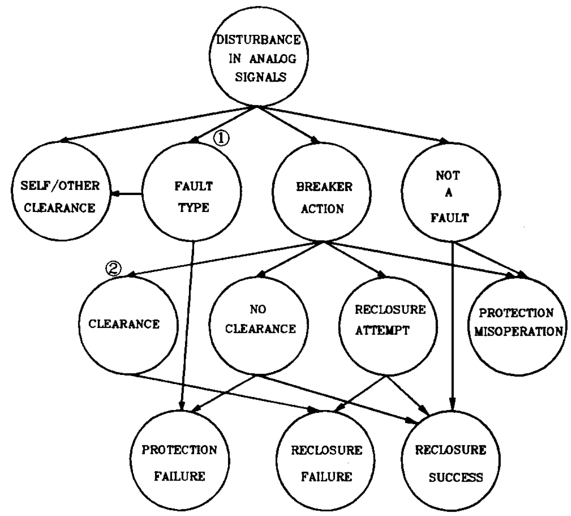

Fig. 1. Event Analysis Rules

Fault classification is based on analog parameter thresholds determined in the testing process. In order to determine these thresholds, further adjustments were made to the relations given in Table II. These thresholds were obtained by dividing the left-hand side quantity with the right-hand side quantity for each relation found in Table II. Thresholds are given in Table III. Finally, some values for thresholds were selected for each of the substations under study.

Table II. Behavioral Patterns of the Basic Parameters

Event Type	0 Seq. Current	Faulted Current	Unfaulted Current	0 Seq. Voltage	Faulted Voltage	Unfaulted Voltage	Line Voltage
AGF	$I_0 > \frac{I_a}{5}$	$I_a > 1.4I_p$	$I_{b,c} < \frac{I_a}{3}$	$V_0 > \frac{V_n}{25}$	$V_a < \frac{9V_a}{10}$	$V_{b,c} > \frac{96V_n}{100}$	$V_{ab} \approx V_{ca}$
ABF	$I_0 < \frac{I_a}{100}$	$I_a > 1.4I_p$ $I_b > 10I_p$	$I_c < \frac{I_a}{10}$	$V_0 < \frac{V_n}{100}$	$V_a < \frac{8V_n}{10}$ $V_b < \frac{7V_n}{10}$	$V_c > \frac{99V_n}{100}$	$V_{ab} < \frac{8V_{luf}}{10}$
ABGF	$I_0 > \frac{I_a}{10}$	$I_a > 1.4I_p$ $I_b > 10I_p$	$I_c < \frac{I_a}{10}$	$V_0 > \frac{V_n}{20}$	$V_a < \frac{8V_n}{10}$ $V_b < \frac{8V_n}{10}$	$V_c > \frac{98V_n}{100}$	$V_{ab} < \frac{8V_{luf}}{10}$
TPF	$I_0 < \frac{3I_b}{100}$	$I_f > 10I_p$		$V_0 < \frac{V_n}{100}$	$V_f < \frac{8V_n}{10}$		$V_{lf} < \frac{8V_{ln}}{10}$
TPGF	$I_0 < \frac{3I_b}{100}$	$I_f > 10I_p$		$V_0 < \frac{V_n}{100}$	$V_f < \frac{8V_n}{10}$		$V_{lf} < \frac{8V_{ln}}{10}$

- AGF: Phase A to Ground Fault
- ABF: Phase A to Phase B Fault
- ABGF: Phase A to Phase B to Ground Fault
- TPF: Three Phase Fault
- TPGF: Three Phase to Ground Fault

- ϵ: A small threshold value to be chosen
- E_1, E_2: Large threshold values to be chosen
- I_{max}: Maximum fault current amplitude

Table III. Threshold Relation Summary

Basic Relation	Threshold
$I_0 \approx 0$	$I_0/I_{max} < \epsilon$
$I_0 > 0$	$I_0/I_{max} > \epsilon$
$I_f > I_p$	$I_f/I_p > E_1$
$I_{uf} \approx I_p$	$I_{uf}/I_p < E_2$
$I_{uf} < I_f$	$I_{uf}/I_f < E_2$
$I_{f_1} \approx I_{f_2}$	$\frac{I_{f_1} - I_{f_2}}{I_{f_1}} < \epsilon$
$V_0 \approx 0$	$V_0/V_n < \epsilon$
$V_0 > 0$	$V_0/V_n > \epsilon$
$V_f < V_n$	$V_f/V_n < E_1$
$V_{uf} > V_f$	$V_{uf}/V_f > E_2$
$V_{lf} < V_{luf}$	$V_{lf}/V_{luf} < E_1$
$V_{luf_1} \approx V_{luf_2}$	$\frac{V_{luf_1} - V_{luf_2}}{V_n} < \epsilon$

It shall be noted that relations derived in Table III are generic expressions and can be used for any type of system but the threshold values have to be determined for each particular system.

Based on the signal parameter values and thresholds, classification rules that provide the fault type can easily be defined. Figure 2 provides an example of a rule used to classify a single phase to ground fault.

Breaker action analysis (Figure 1) determines breaker behavior in the course of the event and it is based on analog signal parameters and the fault detection. This analysis determines fault clearance, reclosure, and the correctness of the protection system operation. Breaker action analysis consists of investigating the zero current level. Table IV describes breaker action analysis. Each event is divided into three intervals, namely, predisturbance, disturbance, and postdisturbance one. This table relates current level patterns and the fault detection indication for each significant event.

Zero current detection provides accurate indications of breaker action. If the breaker was opened after the fault, the fault was cleared. If it was opened before the disturbance, the event was a reclosure attempt. Breaker action in a case of 'no fault' disturbance indicates protection system misoperation. No breaker action in case of a fault may indicate protection system failure.

```
(defrule phase_A_ground_fault
   (ground fault)
      (test (> ?Ia (* 1.3 ?Iap)))
      (test (< ?Ib (* .5 ?Ia)))
      (test (< ?Ic (* .5 ?Ia)))
      (test (< (abs (- ?Ia ?I0)) (* .96 ?Ia)))
      (test (> ?V0 (* 10 ?V0p)))
      (test (< ?Va (* .95 ?Vap)))
      (test (> ?Vb (* .95 ?Vbp)))
      (test (> ?Vc (*. 95 ?Vcp)))
      (test (< (abs (- ?Vb ?Vc)) (* .05 ?Vbp)))
      (test (< (abs (- ?Vab ?Vca) (* .2 ?Vabp)))
      (test (< (abs (- ?Vbc ?Vbcp)) (* .2 ?Vbcp)))
=>
   (assert (phase_A ground fault))
   (fprintout t " Single line to ground fault, phase A" crlf))
```

Fig. 2. Rule for Classification of Single Phase to Ground Fault

Table IV. Breaker Action Anlysis

EVENT DESCRIPT.	CURRENT LEVEL		
	Pre–Disturb.	Fault Detection	Post–Disturb.
Clearance	Any	Yes	0
Reclosure Failure	0	Yes	0
Reclosure Success	0	No	High
Protection System Failure	Any	Yes	High
Protection System Misoperation	Any	No	0
Self/Other Clearance	Any	Yes	No Fault

Figure 3 provides a summary of rules for analysis of the protection system operation. These rules indicate the operation of primary and backup relays, and the operation of main and mutual (middle) breakers. By using the event descriptions made by the event analysis rules and by using the relay communication contact data, protection system operation analysis rules indicate misoperation and failure of breakers and relays. An example of a protection system operation analysis rule is given in Figure 4.

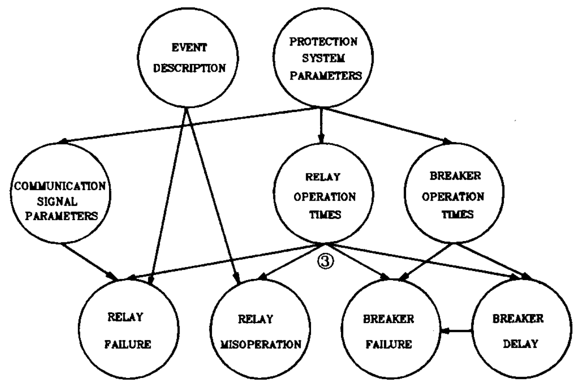

Fig. 3. Rules for Analysis of Protection System Operation

```
(defrule relay_misoperation
   (declare (salience -10))
     (relay ?relay operation ?)
=>
   (assert (relay ?relay misoperation))
   (fprintout t crlf "It is a " ?relay" relay misoperation." crlf
  "Because the event is not a fault and the relay operated." crlf)
)
```

Fig. 4. A Rule for Analysis of Protection System Operation

This rule states that if there is no fault and the primary relay operates, then there is a misoperation of the primary relay.

EXPERT SYSTEM IMPLEMENTATION

One of the main implementation requirements was the interfaces for expert system testing and user interaction. A block diagram of the system is given in Figure 5. The EMTP conversion function is intended for system testing purposes and the user interface function is designated for presentation of the results and modification of the knowledge base.

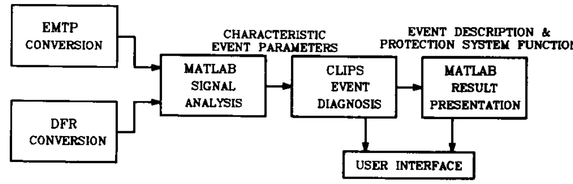

Fig. 5. System Block Diagram

It has been recognized that extensive expert system testing is required to determine thresholds for analog values and to generate enough scenarios of interest. Thresholds are unique to each substation and have to be selected based on a number of fault studies using either EMTP, or a sufficient number of DFR records. Scenarios of interest include various types of faults, fault locations, incidence angles, variations in fault resistance, different line loadings and a variety of system switching configurations since they all affect parameter values.

User interface is the most important feature because it provides the operator with the results of expert system analysis. Since expert system operation may be inconclusive for some "new" events that do not have corresponding rules imbedded in the system, it is important that the operator is presented with all the relevant data used in the inference process. The EMTP output file conversion program is a 'C' language program developed to convert the EMTP output file into the MATLAB binary format.

EMTP simulations are instrumental in testing fault detection and classification function of the system. Its important feature is that it enables simulation of power signal transients generated by a disturbance or a fault.

The EMTP output file is an ASCII format file that includes simulation results. This output file contains the output signal waveform samples, an interpretation of the input file, steady state values, configuration descriptions, plots, etc. It also has some text overhead. The conversion program extracts signal waveform samples, the sampling rate, and names of the EMTP output signals that are required for further processing.

The Digital Fault Recorder (DFR) conversion block indicates file conversion software that takes DFR files and transforms them into MATLAB files. Conversion software inputs are:

- DFR data file. It holds coded contact, current, and voltage samples.
- DFR configuration files. They hold analog channel abbreviations, machine serial number, machine id, sampling frequency, event size, number of pretrigger samples, scaling information, signal dimension information, normal contact status, substation name, number of digital channels.
- Event header file. It holds event specific data and DFR configuration data. For example, the event time stamp, event number, triggering signal, and some repeated configuration data like the sampling frequency.

Outputs of the conversion software are:

- Analog data file. ASCII format file with scaled current and voltage samples in a matrix format ready for loading into MATLAB.
- Digital data file. ASCII format file with contact status samples in a matrix format ready for loading into MATLAB.
- Tables with analog and adopted digital channel name abbreviations.
- Table with analog data dimensions.
- Tables that encode digital and analog signal positions in the data files.
- Conversion sample start and sample end.

The DFR conversion program is written in 'C' programming language. Program command line parameters are: the event number and range of samples to be converted. It converts data recorded into a format suitable for analysis. Initially, DFR data is available in a set of several 32KB binary files. This set of files is concatenated into one binary file to be used as input for the conversion program.

The signal analysis module performs the analysis of analog and digital signals obtained from DFR event and EMTP output files. It is written in the MATLAB programming language and runs within the MATLAB environment [12]. Its inputs are files generated by the data conversion modules described. Its outputs are MATLAB binary format files with the following data:

- Name of the circuit with greatest current disturbance and the disturbance range.
- Analog signal parameters: Analog signal amplitudes within and out of the disturbance range for this circuit.
- Protection system parameters: Contact operation description parameters.

Event diagnosis is implemented using CLIPS, a rule-based expert system shell [13]. CLIPS decision process is schematically described in Figure 6.

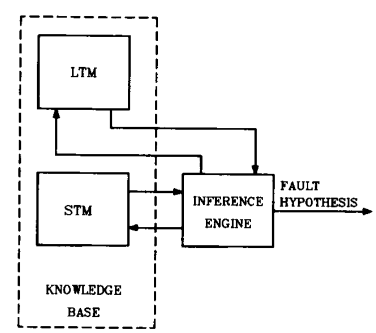

Fig. 6. Expert System Decision Process

The knowledge base consists of a long term memory (LTM) and the short term memory (STM). LTM consists of a set of small knowledge modules that hold representations of the knowledge. Knowledge modules are used in the decision process. These modules are called production rules. Rules have the "if-then" form. If the first part of the rule (premise) is satisfied, then the second part (conclusion) can be derived. Required signal parameters obtained from the signal analysis block and the intermediate results of the decision process are kept in STM. The decision process is performed by the inference engine. According to the current status of STM, a set of rules is activated and only one rule is chosen at a time to make a conclusion in the inference process. Whenever this conclusion is an intermediate one, it is posted in the STM. The process terminates when the set of activated rules is empty.

CLIPS is embedded in an interface implemented using a 'C' program. 'C' program loads MATLAB binary format files with parameters from the analysis module. It converts this data into a format suitable for use by CLIPS, initializes and executes CLIPS.

Result presentation module is also written in the MATLAB command language. It is designed to show signals of interest: current, phase and line voltage waveforms, amplitude waveforms, and breaker, relay and communication contact status waveforms for the line with greatest current disturbance. These signals may be inspected in order to verify the diagnosis provided by the CLIPS block. They are extracted from the large number of recorded signals as characteristic waveforms for a given event.

PERFORMANCE DEMONSTRATION

To demonstrate the expert system performance, a description of the expert's problem solution approach, the expert system reasoning process and the graphical explanation for two real events is given.

Both events were recorded at the South Texas Project (STP) Substation. The first event is a simple single line to ground fault cleared at the STP Substation. The second event is a 'no fault' disturbance event with relay operation.

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.

A one line diagram of the STP Substation is given in Figure 7. For the first event, engineers would notice that the phase A current (Figure 8a) of the circuit 39 to Lon Hill shows the greatest amplitude. Comparing this change to changes in the other phases for this line, they would conclude that the event is a phase A to ground fault. Zero signal level registered after the disturbance indicates that this fault was cleared by the protection system at this substation. Breaker and relay signals for this circuit (Figure 8b) indicate that the primary relay and both breakers operated on time.

For the second event, currents in circuit 39 to Lon Hill have the greatest amplitude change. Inspection of these currents (Figure 9a) and the corresponding voltages indicates that there was not a fault in the system. The disturbance was caused by breaker action. Inspection of the protection system signals (Figure 9b) indicates primary relay operation for a steady no fault state of the system.

Expert system's responses for both events are given in Figures 8c and 9c respectively. These event descriptions coincide with the engineer's descriptions. Some intermediate reasoning

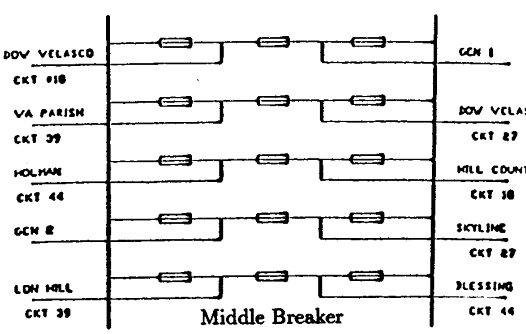

Fig. 7. One–Line Diagram of STP Substation

results and accurate timings are also given and they aid in an efficient inspection of the protection system operation.

To provide a feeling for the expert system's reasoning process, some key steps of the rule chains executed for both events are sketched in Figures 1 and 3.

For the first event, the fault classification rule (Step 1, Figure 1) is given in Figure 2. This rule uses the fact that it is a ground fault and that voltage/current pattern indicates phase A to ground fault. Step 2, Figure 1 consists of a rule stating fault clearance at the STP Substation (Row 2, Table IV). Step 3, Figure 3 does not result in detection of any incorrectness of the protection system operation.

For the second event, a fault detection rule (Row 1, Table I) uses the voltage/current pattern to indicate that the event is not a fault. A breaker action rule (Row 5, Table IV) indicates that there must be a protection misoperation. Protection system analysis rule given in Figure 3 states the primary relay misoperation.

Expert System's diagnosis is followed by a display of significant event signals. This display aids operators to quickly verify system's detection and diagnosis performance.

OVERALL PERFORMANCE ASSESSMENT

Besides the two demonstration examples given in the previous section, the expert system has been tested using a number of other events.

The first group of tests cases was used to tune threshold values for voltage and current parameters. This set of cases included 12 DFR events recorded at 2 HL&P substations and 11 events simulated using EMTP representing a section of the HL&P power system. In addition, 2 DFR events from a different power system and 10 EMTP events from an artificial power system were also used. The main problem at this stage of development was to find the threshold values that are applicable to all of the mentioned events which included a variety of power

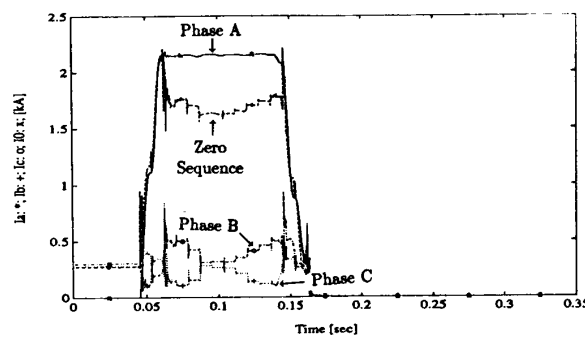

Fig. 8a. AG Fault to Lon Hill: Current Amplitudes at STP

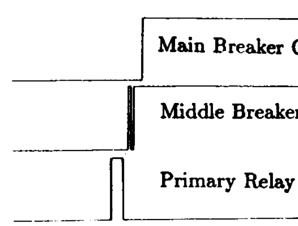

Fig. 8b. AG Fault to Lon Hill: Contacts at STP

EVENT DESCRIPTION USING ANALOG DATA

- LH39 is the circuit with largest current disturbance.
- The disturbance is a ground fault.
- The disturbance is a phase A to ground fault.
- The fault is cleared by the protection system at this substation.

PROTECTION SYSTEM OPERATION ANALYSIS

- Primary relay operation starts at 0.113 and ends at 0.127 seconds.
- The middle breaker opens at 0.146 seconds.
- The main breaker opens at 0.132 seconds.
- The main breaker delay is 0.019 seconds.*
- The middle breaker delay is 0.033 seconds.*

* 52b Contact Operating Time

Fig. 8c. A–Phase to Ground Fault Display

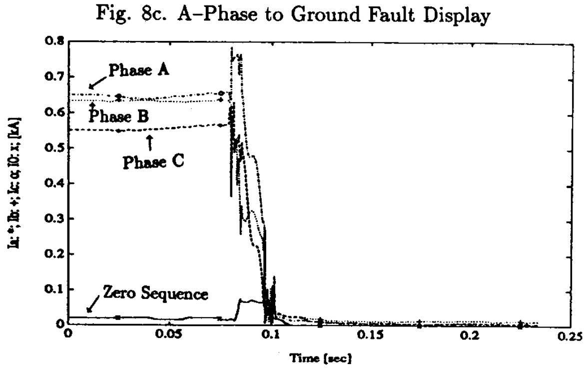

Fig. 9a. Relay Operation to Lon Hill for No Fault on System: Current Amplitudes at STP

EVENT DESCRIPTION USING ANALOG DATA

- LH 39 is the circuit with largest current disturbance.
- The disturbance is not a fault.
- Protection operation but there is no fault.

PROTECTION SYSTEM OPERATION ANALYSIS

- Primary relay operation starts at 0.055 and ends at 0.07 seconds.
- The middle breaker opens at 0.089 seconds.
- The main breaker opens at 0.074 seconds.
- The main breaker delay is 0.019 seconds.
- The middle breaker delay is 0.034 seconds.
- It is a primary relay operation but the event is not a fault.

Fig. 9c. No Fault Disturbance with Relay Operation

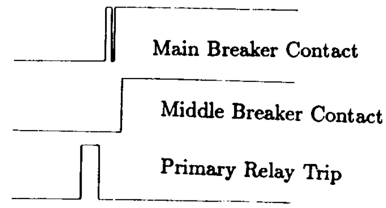

Fig. 9b. Relay Opertion to Lon Hill for No Fault on System: Contacts at STP

system configurations, fault events and system loadings. Once this design testing stage was accomplished, the performance testing was initiated.

The performance tests included 12 DFR cases from the HL&P system and 48 EMTP cases from a different power system. The expert system interpreted all of the events correctly except one DFR event from the HL&P system. This event was rather unique since it represented a fault which was far away from the substation where the recording was made. Also, overall power system configuration provided a ring connection which was feeding this fault in such a way that the expert system saw behavior of the currents which was opposite to the expected one.

As a result of the overall performance assessment, it is important to note that both the developers and the operators felt very confident that the performance of the expert system prototype is outstanding and that it is ready to be installed in the field for further testing and evaluation. This impression about the expert system performance came primarily from the fact that the system was capable of a quick analysis which was much faster than what the operators could do otherwise. In addition, the responses were illustrated by displays of both analog signal and contact parameters. This enabled operators to easily follow and verify the analysis process undertaken by the expert system. The capability of quick analysis and clear result displays was considered by the operators most desirable. The quick automated analysis eliminates the tedious task of the operators trying to sift through a number of events before they find the one of interest. Also, going through an analysis of a selected event may be demanding in itself since DFR records are not necessarily either organized or displayed in a way that facilitates this analysis. The expert system capability to display not only the waveforms and contacts but also their parameters used for the analysis gave the operators confidence that they can verify, if needed, all the results of the automated analysis. This has eliminated the concern that the operators may be grossly misled by a systematic error in the expert system design. As a matter of fact, the operators can use this system as an automated aid whose results for the most critical events can always be quickly checked by the operators since the line of reasoning is clearly illustrated by the expert system displays.

As a final conclusion about the overall performance, it is important to recognize that the expert systems are only as good and reliable as the rules used are correct and complete. The most important experience of this development is related to the process of defining the rules by formalizing the expertise of the operators. It was learned that if this process is performed in a comprehensive manner, the chances of an expert system performing correctly are indeed high. The comprehensive approach assumes detailed analysis of a number of possible events in a given system, extensive simulation of the events using EMTP, and thorough validation of the expert system performance using an extensive number of DFR records obtained in a substation over a long period of time. Hence, the final performance of the expert system development reported in this paper will only be possible after the field experience is monitored and analyzed. The results of this stage will be published in a future paper.

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

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