Expert System Reasoning Streamlines Disturbance Analysis

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Houston Lighting & Power funded Texas A&M to develop an expert system that would provide major time savings and performance improvements

Many utilities have been using digital fault recorders (DFRs) to capture disturbances. The DFR records are then transmitted over communication channels to a protection engineer for analysis. Analysis is related to verification of the protection system and circuit breaker operation. This practice is time consuming due to the large number of records captured and the time required for record transmission and analysis. Houston Lighting & Power Company (HL&P) estimated that further automation would provide significant time savings and performance improvements in the overall disturbance analysis task.

HL&P funded Texas A&M University to develop an automated disturbance analysis system that would satisfy the following requirements:

- PC-based system for substation application
- Direct interface to the existing DFR system
- Graphical user interface (GUI) for viewing of results
- Database management for storing results
- Modem interface to the protection engineer.

The system was developed and extensively tested using Electromagnetic Transient Program (EMTP) simulations and actual disturbance records captured by DFRs at various substations. Since then, the system has been connected to a substation DFR for online monitoring of disturbances.

This article points out some design and implementation issues and highlights performance validation and operating experience related to the expert system.

Knowledge Acquisition and Rule Definition

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

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

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

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

Event and protection system operation analysis includes the following checks:

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

> ***The reasoning process includes fault detection, fault classification, event analysis, and protection system operation analysis***

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

A typical set of rules based on the analog parameters is shown in Figure 1. A sequence of checks is indicated by the circled numbers next to the rule definitions.

Expert System Implementation

The expert system block diagram is shown in Figure 2. The data conversion block translates the format of data generated by the EMTP and different DFRs into a format suitable for analysis performed by a commercial signal-processing package, MATLAB. Additional substation description interface is developed to make up for insufficient EMTP/DFR configuration data. A MATLAB program analyzes raw data to provide parameters required for the diagnostic process. CLIPS, an expert system shell, takes data from MATLAB to make final conclusions regarding the fault detection and diagnosis. EMTP is used to generate test data through simulation, while DFRs are used to collect actual data in a substation.

Event diagnosis in CLIPS is performed by using rules in a forward chaining mechanism. This mechanism uses analog-signal and protection-system operation parameters calculated in MATLAB. These parameters are voltage and current rms values, as well as breaker, relay, and communication contacts for the transmission line that experienced the largest current disturbance. This data is extracted from the set of substation transmission

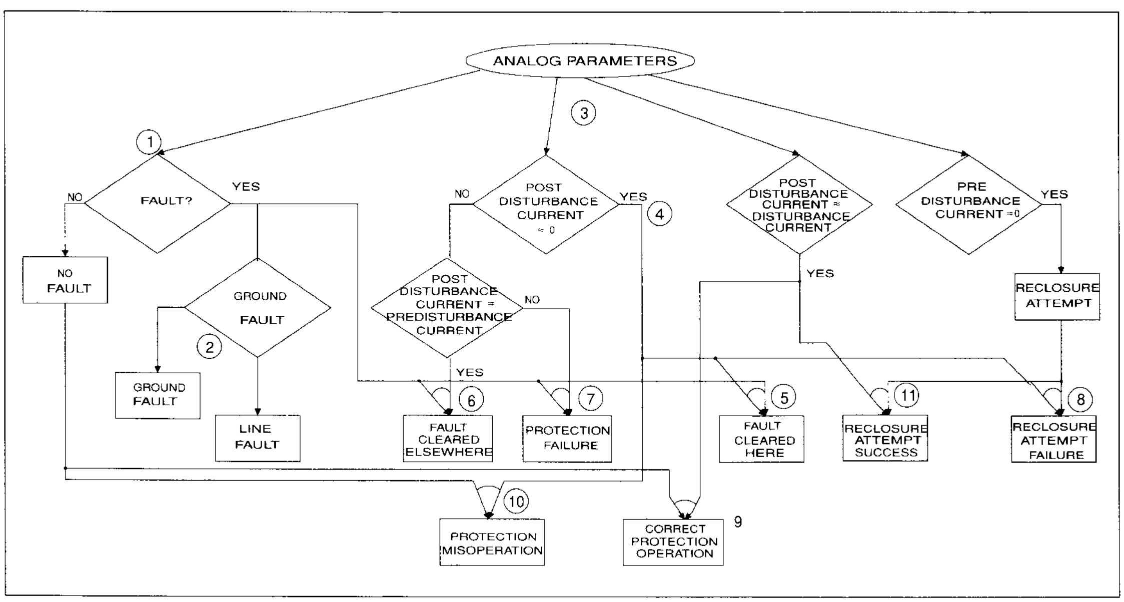

Figure 1. Rules for fault detection, classification, and general event analysis using analog parameters

line data by MATLAB. It also distinguishes the three characteristic time intervals of the event: predisturbance, disturbance, and postdisturbance. The voltage and current rms values for the three time intervals are calculated as the analog-signal parameters. MATLAB identifies incidence of breaker and relay change of status as protection system parameters. It also analyzes the communication signal operation intervals to identify the communication protection system parameters.

The knowledge base was built by interviewing experts and using an empirical approach based on EMTP simulation

Text messages and GUI screens serve as a final expert system output. There are several different levels of information that are given through GUI. Altogether, this information includes a complete step-by-step reasoning process performed by the CLIPS shell, as well as a plot of voltage and current waveforms for a transmission line experiencing disturbance, including circuit breaker and communication channel contacts.

A typical example of a text message for an actual disturbance record captured by DFR at the South Texas Project (STP) substation is shown in Figure 3. It consists of three parts:

- General information (e.g., date/time of the recording, DFR configuration data, record size, etc.)
- Hypothesis about nature of the recorded event
- Protection-system operation analysis.

In addition, several different signal waveform plots are produced to corroborate textual information. An example of a waveform display used to supplement the reasoning process for the event described in Figure 3 is shown in Figure 4. Since the event is characterized as phase A to ground fault at circuit Holman 44, only phase A current for that circuit is displayed, correlated in time to the corresponding digital channels.

Performance Demonstration and Operating Experience

The first group of test 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 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 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 that was far away from the substation where the recording was made. The overall power system configuration provided a ring connection that was feeding this fault in such a way that the expert system saw behavior of the currents opposite to what was expected.

As a result of the overall performance assessment, it is important to note that both the developers and the

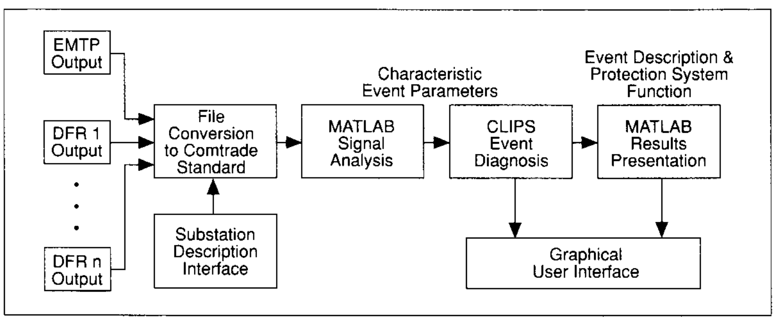

Figure 2. Expert system block diagram

Date\Time Stamp of Event: **06/28/93, 00:02:18.760**

Total number of channels: 56
Number of analog channels: 48
Number of digital channels: 128

Event number: 002
Machine ID: C25N
Sample rate: 5.99 [kHz]

Number of pretrigger samples: 1198 (12.0 cycles)
Total number of samples: 2926 (29.3 cycles)
Size of the event in tracks: 10 (320Kb)
Machine name: S.T.P.
Serial number: 20299
Converted 1755 samples starting from sample 900.

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

Holman 44 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 0.0742 sec [4.4502 cycles] and ends at 0.0908 sec [5.4498 cycles].
The middle 52B contacts operates at 0.1005 sec [6.0300 cycles].
The bus 52B contacts operates at 0.1025 sec [6.1500 cycles].
The bus breaker status change is 0.0283 sec [1.6998 cycles].
The middle breaker status change is 0.0263 sec [1.5798 cycles].

Figure 3. Disturbance record text message

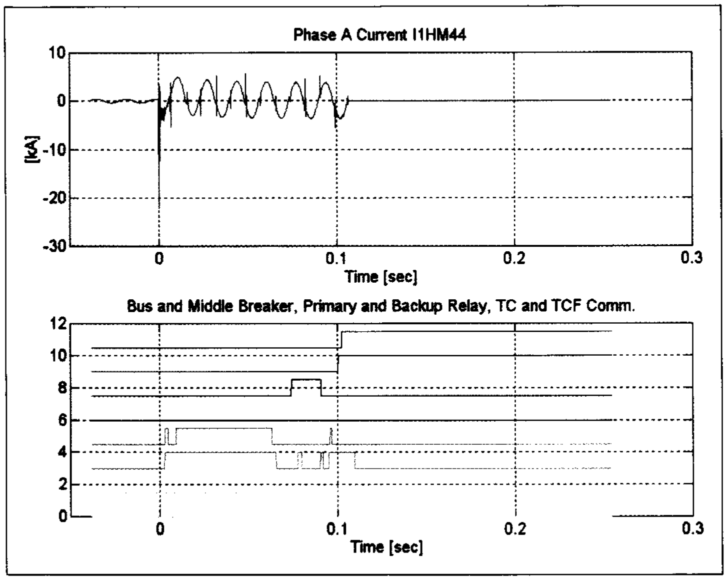

Figure 4. Signal display used to illustrate the reasoning process performance demonstration and operating experience

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.

Presently, the system is connected to the South Texas Project (STP) substation. A one-line diagram of the substation is shown in Figure 5. STP is a 345 kV substation with two generators, and it connects ten transmission lines. The DRF unit installed at the STP substation monitors currents for all lines and voltages for both buses.

Further evaluation of the expert system logic is under way by using a remote connection between the STP substation and Texas A&M University. This configuration is shown in Figure 6.

Communication between the expert system computer and the STP substation DFR is facilitated using TR1625 master station software. Every recorded event at the STP substation is retrieved and archived at the expert system computer.

Upon completed retrieval of an event, classification and analysis are executed, and the report is generated and stored. The report consists of textual descriptions of an event and of graphical files (in the MATLAB format). These graphical files are processed using MATLAB 4.0 and converted into standard encapsulated postscript (EPS, which is used for printing) and PC Paintbrush (PCX) formats.

Communication with HL&P's office in Houston is realized using PC Anywhere software. The expert system computer, in this case, serves as a host machine. HL&P retrieves archived reports at their convenience.

A simple record database is built and maintained using Paradox for Windows. An example of a database entry, corresponding to the event described in Figures 3 and 4, is shown in Figure 7.

Eventually, the expert system will be located at the STP substation, and the link to Texas A&M University will cease to exist. When that happens, short messages similar to the ones shown in Figure 3 will be sent to HL&P in Houston. This will replace the existing practice in which a stream of recorded data is sent from the STP substation to HL&P once an operator dial-up call from HL&P offices is placed.

Depending on the length of the DFR record, the expert system will need between 1.5 and 3 minutes to complete the analysis locally at the substation and generate condensed report (see Figure 3). The size of the report is not greater than 2K bytes, which is negligible compared to the size of the original DFR record (ranging from 256K to 800K bytes). Potential savings in time and manpower are almost obvious.

The operating experience is gained based on 39 actual disturbances recorded at the STP substation since June 1993. The expert system has recognized most of the fault disturbances and has provided correct conclusions. Some disturbances were encountered that were not covered by the rules that were built during the design peri-

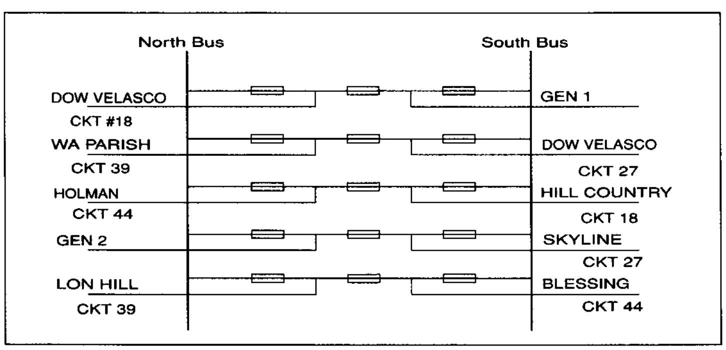

Figure 5. One-line diagram for the STP substation

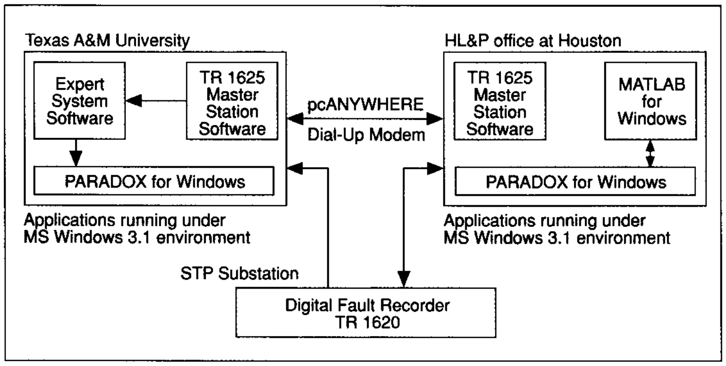

Figure 6. Initial expert system testing using direct connection to the STP substation

od, and the system rule base was extended to cover those cases as well.

For Further Reading

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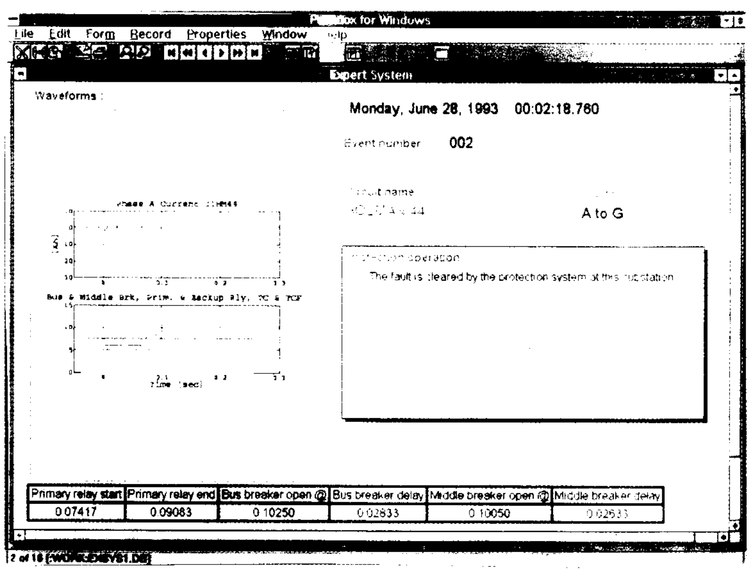

Figure 7. Database form for event recorded at the STP substation

Biographies

Mladen Kezunovic received his Dipl. Ing. degree from the University of Sarajevo, Yugoslavia, the MS and PhD degrees from the University of Kansas, all in electrical engineering in 1974, 1977, and 1980, respectively. His industrial experience is with Westinghouse Electric Corporation in the United States and the Energoinvest Company in Yugoslavia. His academic experience is with the University of Sarajevo, Washington State University, and Texas A&M University. He is an IEEE senior member, a member of the IEEE PES Power System Relaying Committee, and chair of the Working Group on Application of Intelligent System Applications in Protection Engineering and the Working Group on Digital Simulators for Relay Testing. He is a registered professional engineer in Texas.

Igor Rikalo received his Dipl. Ing. degree from the University of Sarajevo, Yugoslavia in 1992. He is a graduate student in the Electrical Engineering Department, Texas A&M University, working towards his MS degree in the area of intelligent system applications.

Charles W. Fromen received a BSEE from Texas A&M University in 1968. Upon graduation, he joined the HL&P Distribution Relay Protection group. He was reassigned to the Transmission & Generator Relay Protection group in 1972. Since 1984, he has been a senior consulting engineer. He is the HL&P technical representative for the East Tie HVDC Project. He has been the HL&P representative to the IEEE Power Systems Relaying Committee since 1973 and is a member of that committee. He is an IEEE senior member and a registered professional engineer in Texas.

Donald R. Sevcik received his BSEE from Texas A&M University in 1975. He joined HL&P in 1975 and is presently a lead engineer. He has worked in the areas of power plant electrical systems (1975 to 1977), system studies (1977 to 1979), and transmission and generation protection (1970 to present). He is an IEEE member and a registered professional engineer in Texas. He is a former officer of the PES Houston Chapter.