Automated Analysis of Digital Relay Data Based on Expert System

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***Abstract*—Modern digital protective relays generate various files and reports which contain abundant data regarding fault disturbances and protection system operation. This paper presents an expert system based application for automated analysis of digital relay data. In this application, forward chaining reasoning is used to predict expected protection operation while backward chaining reasoning is employed to validate and diagnosis of actual protection operation. An EMTP/C++ based digital relay model with capability of insertion of user-defined errors and generation of files and reports is developed. The analysis capability of this application is tested using the relay model.**

***Index Terms*—relay operation, relay files, data analysis, expert system, relay model**

I. Introduction

WITH the development of computer and communication technologies, more and more intelligent electronic devices (IEDs) such as digital protective relays (DPRs), digital fault recorders (DFRs), sequence of event recorders (SERs) and remote terminal units (RTUs) of supervisory control and data acquisition systems (SCADAs) are used in power system substations. They supply abundant data related to monitoring, control and protection of power systems. By analysis of these data, very useful information can be generated for system operators, protection engineers and maintenance staff [1]. Sophisticated software tools are required to perform the analysis so that the benefits of these data can be maximized. Since the 80's, expert systems were proposed as a promising tool for analysis of power system data. Various expert system based applications such as DFR data analysis, alarm processing, and circuit breaker monitor data analysis have been reported in the literature [2], [3], [4]. However, most of these applications can not perform detailed analysis of protection system operation because they generally utilize data from DFRs, SERs and RTUs, which only contain limited information about protection system behavior.

In recent years, digital protective relays have gained the capability to generate files and reports which contain detailed data about power system fault disturbances and corresponding responses of protection system components. These data include samples of analog currents and voltages, statuses of protection elements and control elements of relays, statuses of contacts of relays, communication channels and circuit breakers. Automated analysis of these data enables protection engineers to quickly and accurately evaluate operation performance, identify design deficiency and incorrect settings and trace component malfunctions [5].

This paper presents research results related to development of an expert system based application for automated analysis of digital relay data. Section II introduces data contained in the files and reports generated by digital relays. Section III presents the conceptual strategy of the analysis. Section IV describes an implementation of the application. Section V introduces an EMTP/C++ based digital relay model and presents a case study to demonstrate the features of the application by analyzing files and reports generated by the relay model. Section VI draws the conclusions of this paper.

II. Digital Relay Data

Modern digital relays are capable of generating various files and reports, each of which may contain a specific category of data. Generally, oscillography data contain the records of what a relay "sees" during disturbance events. Setting data specifies how the relay is configured. Fault data presents disturbance information and phasor parameters calculated by the relay for its decision making. Sequential event data reveals how the relay and associated protection components actually respond to the disturbance events. These four categories of data are introduced as follows.

A. Oscillography Data

Oscillography data generated by the fault recording function of a digital relay are usually contained in oscillography files in COMTRADE format [6]. Secondary voltages and currents coming into the relay are recorded as analog channels while statuses of both external contacts and internal states of the relay can be recorded as digital channels by users' selection.

B. Setting Data

Setting data contained in a setting file specify configuration parameters of a relay. Usually setting data configures the relay at three levels: selecting protection and control elements, deciding how the selected elements are logically combined, and setting operating parameters of each selected element.

C. Fault Disturbance Data

Fault data contained in a fault report include fault type, fault location and voltage and current phasors during pre-fault and fault periods. They are calculated by a relay and used for its decision making.

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D. Sequential Event Data

Sequential Event Data contained in an event report are time-stamped logic operands in chronological order. It contains most of the information through which the external behavior of a relay and its associated protection system components and the internal states of the relay can be observed. According to our investigation, for some types of relays, not all logic operands that are important for analysis are reflected in their event reports. This problem can be solved if users select these operands to be recorded in the oscillography files.

Besides the above four categories of data, performance specification data such as average operating time for Zone 1 of a distance relay and average operating time of a circuit breaker are also important to our analysis. They are usually contained in user's manuals or may be obtained from other IEDs.

III. Conceptual Strategy of the Analysis

The analysis of relay data is based on comparison of expected and actual protection operation in terms of statuses and corresponding timings of logic operands. If the expected and actual status and timing of an operand are consistent, the correctness of the status and timing of that operand is validated. If not, certain failure or missoperation is identified and diagnosis will be initiated to trace the reasons by the use of logic and cause-effect chain.

Fig. 1 illustrates the conceptual strategy of the analysis. The expected protection operation is predicted by an expert system module which simulates the operation chain of the protection system. Inputs to this module are disturbance information, relay settings and performance specification of protection system components.

Disturbance information includes fault inception time, fault type, fault location and current interruption time after circuit breaker opening. The information may come from several sources: the local relay, remote relays and other fault analysis applications based on advanced algorithms and techniques such as expert systems, Neural Networks and Synchronized Sampling. References [2], [7], [8] provide details of these advanced algorithms and techniques for fault analysis.

To decide the information source to be used in the analysis, we have the following assumptions.

1) The disturbance information obtained from fault analysis applications based on advanced algorithms and techniques is more accurate than that produced by relays.

2) The disturbance information produced by the relay which indicates the fault is in its Zone 1 is more accurate than that produced by the relay which indicates the same fault is in its operation zones other than Zone 1.

Based on above assumptions, the logic for choice of source of disturbance information is illustrated in Fig. 2. Currently this part of logic is not included in our application because we assume the disturbance information is obtained from an expert system based DFR data analysis application [2], [9].

With disturbance information, relay settings and performance specification available, the expected statuses and timings of active logic operands are inferred by forward chaining rules. The results are regarded as hypothesis of protection operation. The actual statuses and timings of operands which are obtained from the oscillography file and event report are the facts of protection operation.

With both hypothesis and facts of protection operation as inputs, an expert system module will first perform validation of the correctness of statuses and timings of logic operands based on hypothesis-fact matching. Then it will further perform diagnosis of inconsistency of expected and actual statuses as well as timings of logic operands based on the logic and cause-effect chain. Finally an analysis report will be generated.

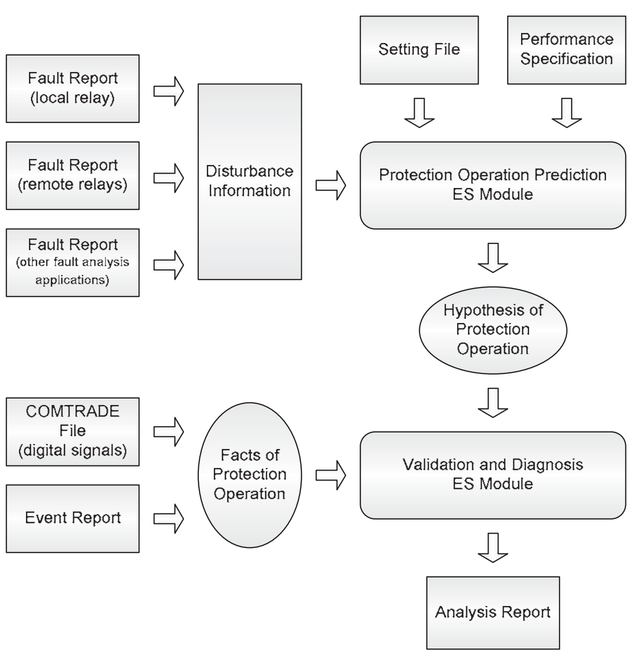

Fig. 1. Block diagram for conceptual strategy of the analysis

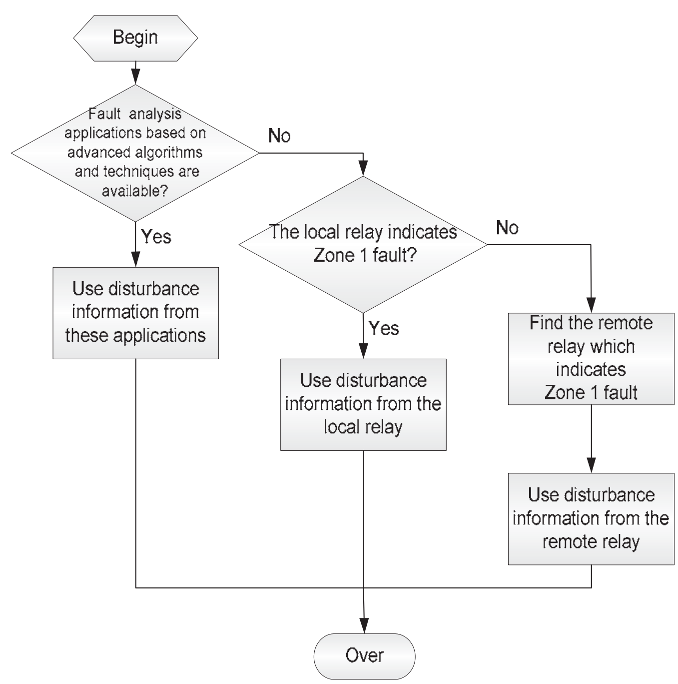

Fig. 2. Logic for choice of source of disturbance information

IV. APPLICATION IMPLEMENTATION

A windows framework is developed using Visual C++ for the application. Data inputs from relay files and reports and data outputs to analysis reports are implemented through the framework. A CLIPS expert system inference engine is linked with the framework by means of Dynamic Link Library (DLL) [10]. The framework takes care of loading the facts and rules into the inference engine and reading the inference results from the engine.

A. *Data Input*

The framework reads the initial facts for the expert system module used for prediction of protection operation from the fault report, the relay setting file and a windows dialog for performance specification input. Then these facts are converted into CLIPS language format.

The framework also reads the facts of actual protection operation for the expert system module used for validation and diagnosis of protection operation from the digital signal section of oscillography file and the event report. In order to generate time-stamped logic operands from the oscillography file which are consistent with those contained in event report, several steps of processing are performed.

1) The digital signals in the oscillography file are converted to time-stamped logic operands by examining their status changes and corresponding timings.

2) The time-stamp of a critical logic operand generated from the oscillography file is compared with that contained in the event report to unify the time base for the oscillography file and the event report.

3) The union of the set of time-stamped logic operands generated from the oscillography file and the set of time-stamped logic operands contained in the event report is chosen to observe the actual protection operation.

B. *Expert System Rules*

Currently the rule base of the expert system is designed for operation of circuit breakers and four protection elements including Phase Distance (PHASE DIST), Ground Distance (GROUND DIST), Phase Instantaneous Over-Current (PHASE IOC) and Ground Instantaneous Over-Current (GROUND IOC).

The rule base includes two parts. One is for prediction of expected protection operation. The other is for validation and diagnosis of actual protection operation. The former is developed according to the protection operation chain which includes seven steps: over-current supervision of individual phases of protection elements, pickup of individual phases of protection elements, operation of individual phases of protection elements, operation of protection elements, relay trip, circuit breaker opening, and current interruption by circuit breakers. The latter are divided into three parts according to their functions. The three functions include validation and diagnosis of statuses of logic operands, evaluation of operating speed of protection elements and associated circuit breakers, and examination whether the relay is tripped by the expected protection element. The rule base built in CLIPS language is stored in a text file. When the analysis is initiated, it is loaded into CLIPS inference engine through the windows framework.

C. *Expert System Reasoning Process*

The reasoning for prediction of expected protection operation is a forward chaining process [11]. Fig. 3 illustrates the reasoning process, which only details the operation of ground distance elements. The time delay parameters such as dT_{SUPN}, $dT_{PKP\_P\_Z}$ and $dT_{OP\_P\_Z}$, which are used to infer the timing relations, are obtained from relay settings and performance specification of the relay and associated circuit breakers.

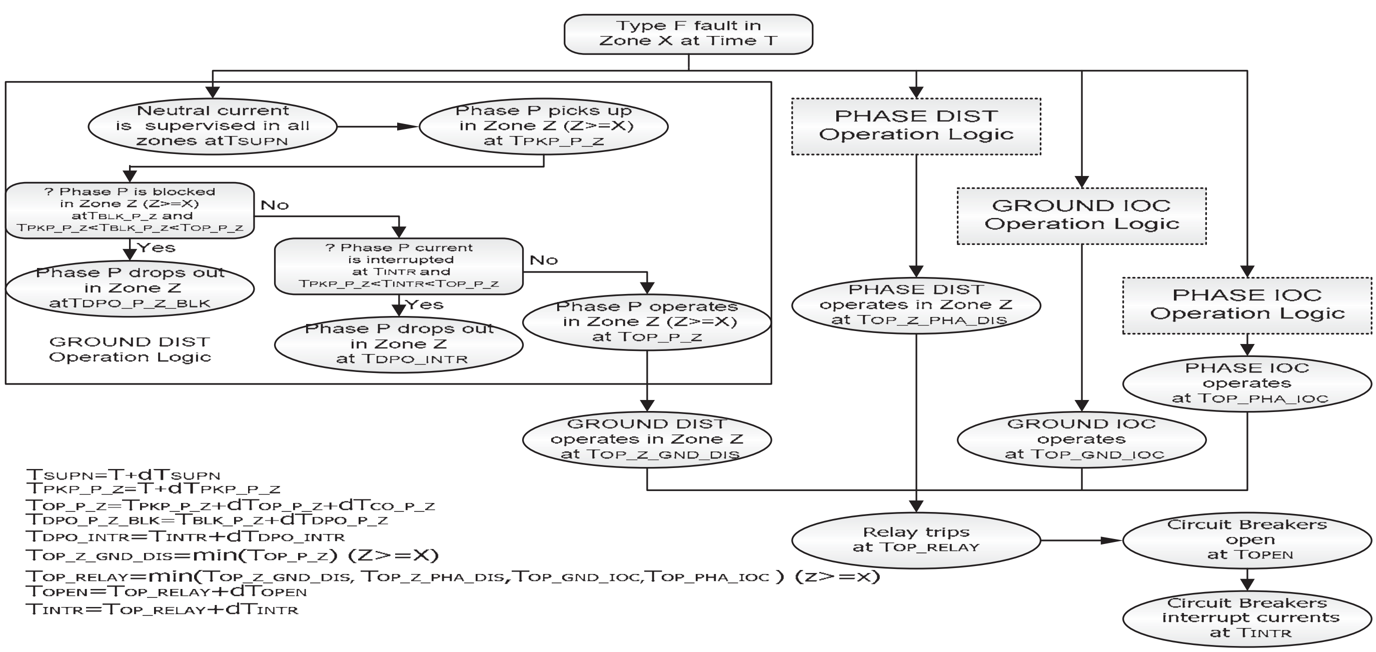

Fig. 3. Reasoning process for prediction of expected protection operation

The reasoning for validation and diagnosis of statuses of logic operands is performed in two stages. Fig. 4 illustrates the reasoning process. In the first stage, the validation of correctness of statuses of logic operands and diagnosis of the direct reason for incorrect statuses is performed at all the steps of the protection operation chain. The validation is based on the existence and non-existence of hypothesis and fact of an operand status. If both the hypothesis and the fact exist, the correctness of the operand status is validated and there is no diagnosis information. If the hypothesis exists but the fact does not exist, a symptom will be identified and the direct reason for the symptom will be diagnosed. In the second stage, the final reasons for symptoms identified in the first stage will be traced in a top-down manner by relating together the direct reasons for symptoms found in the first stage, which is a backward chaining reasoning process [11].

The reasoning process illustrated in Fig. 4 is based on examination of the existence of a fact if the corresponding hypothesis exists, which aims to deal with such symptoms: A status of a logic operand should have existed but it does not exist. There is also a counterpart of the reasoning process, which aims to deal with such symptoms: A status of a logic operand should have not existed but it exists.

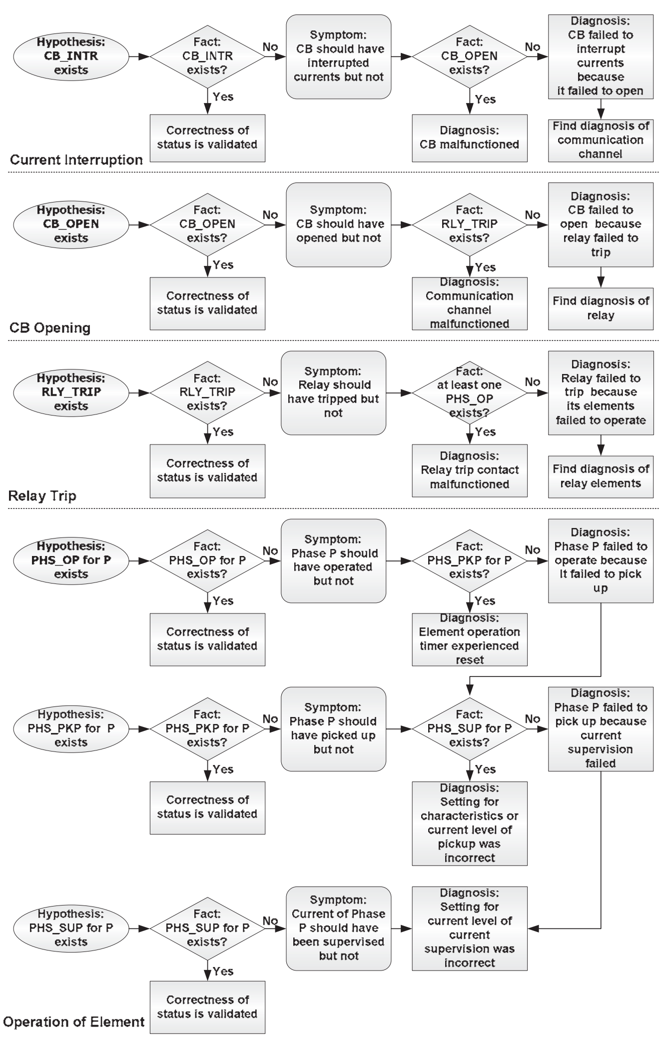

Fig. 4. Reasoning process for validation and diagnosis of status of logic operands

The operating speed of protection elements and associated circuit breakers is evaluated by examining the timings of statuses of logic operands.

With the validation and diagnosis information of statuses of logic operands and operating speed of protection elements available, whether the relay is tripped by the expected element is further examined and the diagnosis is performed.

V. Case Study

In this section, we use a case study to demonstrate the features of the application.

A. EMTP/C++ Based Relay Model

In order to generate the relay data to be analyzed by the application, a digital relay model is developed using C++ language and MODELS language of ATP program [12]. The relay model is integrated into a substation model previously developed using ATP program. The C++ code realizes the relay function as a foreign model and the MODELS code acts as the interface between the relay function and the ATP program which describes the substation model. The relay model has the following features.

1) Inputs of the relay model include up to three channels of node voltages and six channels of branch currents as well as digital signals such as circuit breaker statuses and block signals. Outputs include up to six channels of relay trip signals. Such I/O capability can handle one and a half breaker scheme and single-pole tripping.

2) The relay model has four protection elements: Phase Distance, Ground Distance, Phase Instantaneous Over-Current and Ground Instantaneous Over-Current. Each element can be independently enabled or disabled. The distance elements have three forward protection zones and one reverse protection zone.

3*)* The settings for the relay model are automatically read from a setting file at the beginning of the simulation. An event report and an oscillography file in COMTRADE format are automatically generated at the end of the simulation. The user can select any of the pre-defined logic operands to be recorded in the digital signal section of the oscillography file.

4) Users can insert pre-defined errors into the relay model which can cause failures and missoperation. This feature facilitates testing of the application for relay data analysis.

B. Fault Scenario

Fig. 5 illustrates the I/O connection of the relay model with the substation model. The relay DR01 is protecting the outgoing line L1 which is connected to the substation by one and a half breaker scheme. The relay takes node voltages on Bus B1 as voltage inputs and branch currents through circuit breakers CB1 and CB2 as current inputs. The two circuit breakers are controlled by the relay by means of three-phase tripping scheme. The connection between the relay and the two circuit breakers is simulated by timers within the relay. The statuses of breakers are also monitored by the relay.

Fault location, fault type and fault inception time can be arbitrarily set on line L1. TABLE I lists the fault information used in this case study.

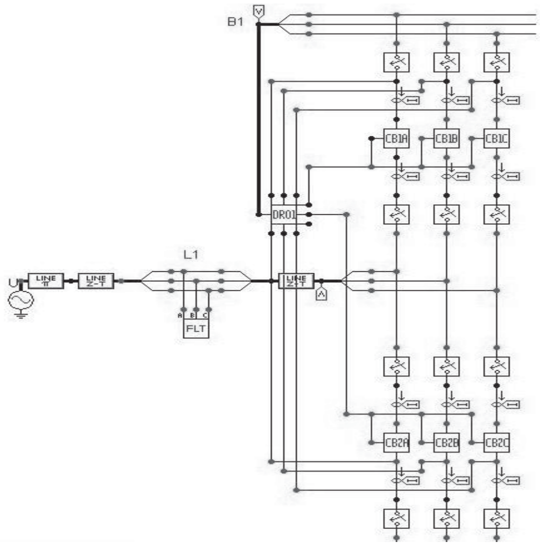

Fig. 5. I/O connection of the relay model with the substation model

TABLE I
FAULT INFORMATION

Fault Type	A-B
Fault Location	82 % (Zone 2)
Fault Inception Time	0.400 second

C. Expected Protection Operation

The relay and associated circuit breakers should respond to the fault according to relay settings and performance specifications. TABLE II lists the major characteristics of expected protection operation.

TABLE II
EXPECTED PROTECTION OPERATION

Operated Element(s)	Phase Distance Zone 2
Relay Trip Time	0.500 second
Circuit Breaker Opening Time	0.532 second
Current interruption Time	No latter than 0.548 second

D. Actual Protection Operation

In order to demonstrate the analysis capability of the application, we have deliberately introduced some errors in the relay model. TABLE III lists those errors.

TABLE III
USER-INTRODUCED ERRORS

1.Incorrect setting of characteristics of pickup of Phase Distance Zone 2 Element
2.Faster opening of Circuit Breaker 1 than performance specification by one cycle period
3.Slower opening of Circuit Breaker 2 than performance specification by one cycle period

After a simulation lasted for 1 second, the relay generates an oscillography file and an event report. Fig. 6 and Fig. 7 show the oscillography file and event report displayed in the GUI of the application respectively. It should be noticed that the oscillography shows the waveform of line currents of line L1, which is the sum of branch currents through circuit breakers CB1 and CB2.

E. Analysis Report

The analysis report is displayed in the dialog shown in Fig. 8. It includes relay information, validation information and diagnosis information. The validation information section lists

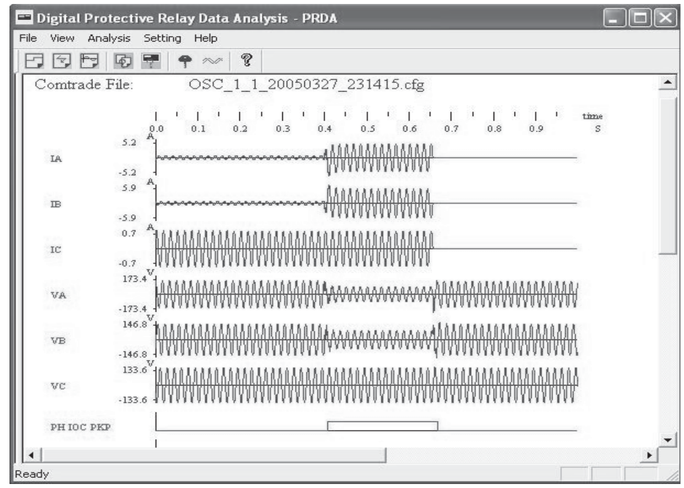

Fig. 6 Oscillography file generated by the relay model

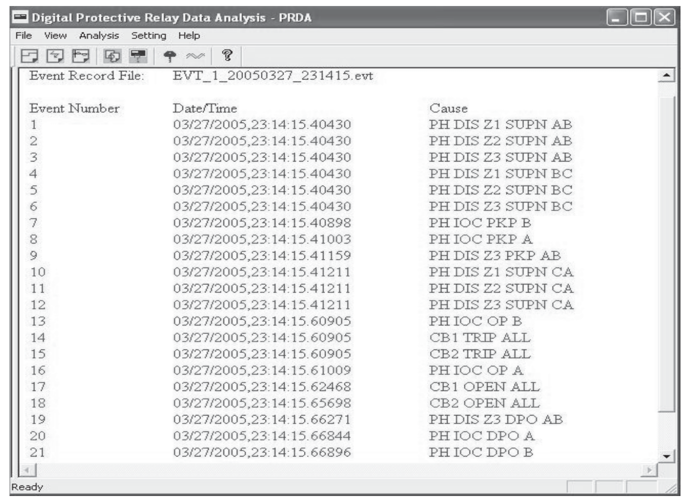

Fig. 7 Event report generated by the relay model

logic operands whose status is as expected and protection elements whose operating speed is as expected. As shown in this section, Phase IOC Element operated to make the relay trip. The circuit breakers opened because of the relay trip.

Three abnormities were identified and diagnosed as shown in the diagnosis information section.

Because Phase Distance Zone 2 Element should have operated but failed to operate, it was the Phase IOC Element instead of Phase Distance Zone 2 Element that made the relay trip. From such information, we may know that Phase IOC Element functioned correctly as a backup for distance elements. Since the operating time delay of Phase IOC Element was set to be 0.1 second longer than that of Phase Distance Zone 2 Element, the relay trip and opening of circuit breakers were delayed nearly 0.1 second. The reason for failure of operation of Phase Distance Zone 2 Element was the incorrect setting of its pickup characteristics.

Circuit Breaker 1 opened faster than expected by 0.016 second while Circuit Breaker 2 opened slower than expected by 0.016 second.

All the three user-introduced errors are identified and diagnosed, which proves the correctness of the analysis.

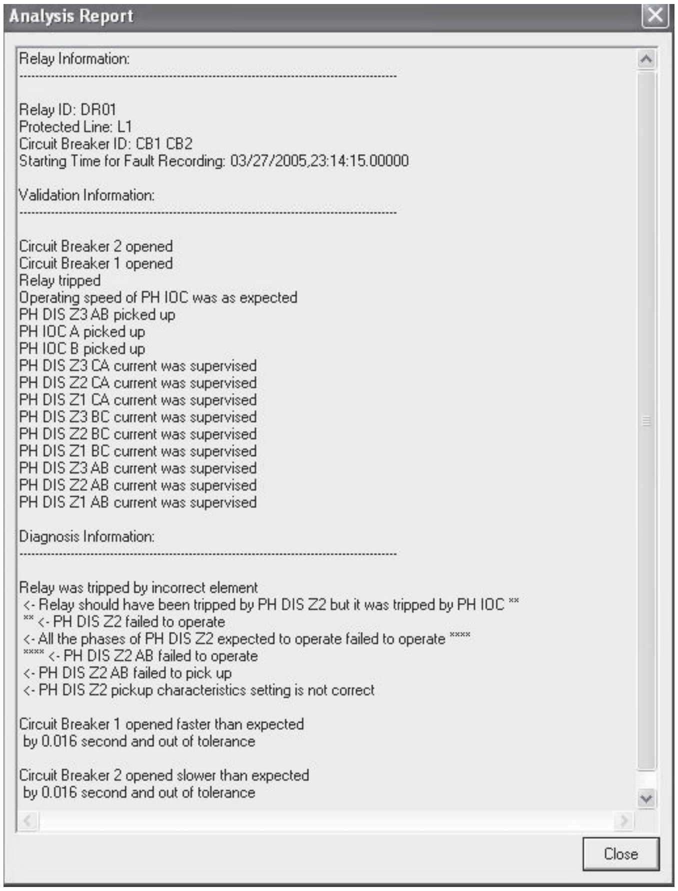

Fig. 8 Analysis report generated by the application

VI. Conclusions

Based on the discussion in this paper, conclusions are drawn as follows:

1) Files and reports generated by digital relays contain abundant data about the external and internal behavior of relays. They are very useful for detailed diagnosis of protection system operation.

2) Expert systems are powerful tools for protection engineers to develop intelligent applications for data analysis.

3) Forward chaining reasoning and backward chaining reasoning have their own strength. Combination of the two makes expert system applications more efficient.

4) MODELS language of ATP program combined with other high level languages such as C++ can model very complicated logic systems such as multifunctional digital relays.

Future work on the improvement of the relay data analysis application includes two steps. First, the knowledge base of the expert system will be expanded to enable analysis of large quantity of relay data and interactions of several relays if pilot protection schemes are involved. Second, one or more fault analysis applications based on advanced algorithms and techniques will be integrated to provide accurate disturbance information.

VII. References

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VIII. Biographies

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