An Expert System for Diagnosis of Digital Relay Operation

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Abstract—**This paper presents an expert system which performs detailed diagnosis of digital relay operation by analyzing data contained in relay files and reports. Problem domain is discussed first. Then the analysis strategy is detailed: Forward chaining reasoning, logic reasoning and backward chaining reasoning are employed to predict protection operation, identify unexpected protection operation and diagnose symptoms respectively. The implementation of knowledge representation by CLIPS rules is further described. Finally an example is given to demonstrate the capability of the expert system.**

Index Terms—**expert system, diagnosis, relay operation, relay files, forward chaining, backward chaining**

I. Introduction

D UE to their strength of reasoning capability, reliability and efficiency, expert systems have been widely used in the fields of business, medicine, science and engineering [1]. Recognizing these successes, power engineers were motivated to investigate the application of expert systems to power system problems since the 80's. Alarm processing, system restoration and reactive power/voltage control are a few areas which early research covered [2]. Since the 90's, expert systems are further proposed as a potential tool for testing, validation and diagnosis of protection system operation. An expert system called RETEX for analysis of relay testing data is reported in [3]. It utilizes predefined fault information and data from a sequence of events recorder (SER) and relay targets to analyze relay operation under simulated faults and compare relative performance of several proposed relays. An expert system based automatic disturbance analysis system that uses data from digital fault recorders (DFR) to perform fault detection, fault classification and verification of protection system operation is described in [4]. An expert system based decision support system (DSS) for protection system performance analysis is discussed in [5]. The DSS interprets data from supervisory, control and data acquisition (SCADA) system, plus data captured by digital fault recorders to perform alarm processing, fault analysis and validation of protection activities.

In recent years, more and more digital relays have gained the capability to generate files and reports which contain abundant data about what they "see" and how they respond during power system faults. These data include sampled analog currents and voltages, status of input and output contacts, status of protection elements and control elements, and relay settings [6]. Compared with data coming from SERs, DFRs and SCADAs, relay data reveal more detailed information about external and internal behavior of relays, therefore enable quite comprehensive diagnosis of relay operation.

This paper presents a prototype expert system which performs diagnosis of digital relay operation based on data contained in relay files and reports. Section II introduces the problem domain which the expert system targets. Section III presents the diagnosis strategy. Section IV describes the system implementation. An example that demonstrates the capability of the prototype expert system is given in Section V. Conclusions are drawn in Section VI.

II. Problem Domain

The problem domain which the expert system targets is the diagnosis of operation of GE's D60 relay with the following four protection elements: Phase Distance (PHS DIST), Ground Distance (GND DIST), Phase Instantaneous Over-Current (PHS IOC) and Ground Instantaneous Over-Current (GND IOC) [7]. Since many digital relays are designed in similar way as D60, the problem domain and the expert system solution have inherent generality.

A. Protection Operation Chain

To achieve maximum flexibility, the firmware of many digital relays is designed using the concept of functional elements. These elements usually include protection elements, control elements and input and output contacts which represent pilot signal statuses and circuit breakers statuses. The statuses of each element are represented by a set of predefined logic operands. As examples, TABLE I shows several logic operands for Ground Distance Zone 1 Element of GE's D60 relay [7].

When fault occurs, functional elements change their statuses according to their design principles and settings. A timed protection operation chain will be formed in order to trip the circuit breaker associated with the relay to interrupt fault currents in time. Fig. 1 illustrates the protection operation chain. In this chain, the over-current supervision of individual phases of protection elements is the first step and the currents interruption by circuit breaker is the last step.

TABLE I
OPERANDS FOR GROUND DISTANCE ZONE 1 ELEMENT OF D60 RELAY

| Operand Syntax	Description
GND DIST Z1 PKP	Ground Distance Zone 1 has picked up
GND DIST Z1 OP	Ground Distance Zone 1 has operated
GND DIST Z1 PKP A	Ground Distance Zone 1 Phase A has picked up
GND DIST Z1 OP B	Ground Distance Zone 1 Phase B has operated
GND DIST Z1 DPO C	Ground Distance Zone 1 Phase C has dropped out
GND DIST Z1 SUPN IN	Ground Distance Zone 1 neutral current is supervised
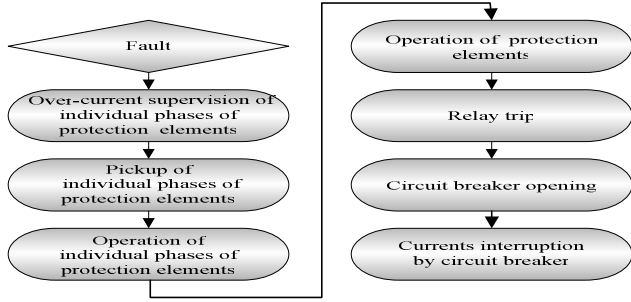
Fig. 1. Protection operation chain

Along the chain, operation of individual phases of a protection element may be blocked by block signals. Operation of any individual phase of a protection element will cause operation of the element. That is to say, operation of individual phases of a protection element triggers operation of the entire element through "or" relation. Likewise, operation of several protection elements also triggers the relay trip through "or" relation.

B. Diagnosis Problem

Due to potential design deficiency, incorrect settings, physical malfunction or subtle fault scenarios, the statuses and corresponding timings of elements may not be as expected. This may cause protection system failure or missoperation. We are generally interested in three levels of diagnosis problems.

First, all the unexpected statuses of elements should be identified.

Second, all the unexpected timings of operation of elements should be identified even if their statuses are correct.

Third, a symptom of unexpected status or timing of an element may be caused by a malfunction of its directly related logic component. It may also be caused by a malfunction of unrelated logic components, because abnormities can propagate through the protection operation chain to cause several occurrences of symptoms. The malfunctioned logic components should be traced out by analyzing the relations of these symptoms.

The first two problems can be solved by comparing predicted statuses and timings of elements with the actual ones. Thus a relay logic model is needed to generate all the expected statuses and timings of elements based on disturbance information, settings and performance specifications. Disturbance information includes fault inception time, fault location, fault type, and circuit breaker

currents interruption time. It is supposed to be provided by external fault analysis functions based on advanced algorithms and techniques [4], [8], [9]. They will not be discussed in this paper.

To solve the third problem, an efficient way is to reason from the effect side to the cause side in cause-effect relations. In terms of the protection operation chain, a reasoning mechanism is needed to traverse from its higher level down to its lower level.

C. Information Inputs for Diagnosis

Except for the disturbance information, the information for diagnosis comes from four common types of relay files and reports. The setting file and performance specification provide input information for prediction of statuses and timings of elements. The event report and oscillography file provide information on actual statuses and timings of elements. These files and reports are summarized in TABLE II.

TABLE II
SUMMARY OF INFORMATION IN RELAY FILES AND REPORTS

File & Report	Description
Setting File	It contains configuration information about the relay at three levels: selecting protection and control elements, deciding how the selected elements are logically combined, and setting the operating parameters of each selected element.
Performance Specification	It contains information about the element operating parameters.
Event Report	It contains a list of time-stamped logic operands in a chronological order.
Oscillography File	It contains analog values of three-phase voltages and currents and digital status of logic operands selected to be recorded by the users. Digital status data provide complementary information on logic operands if some of them are not reflected in the event report but are selected to be recorded in the oscillography file by users.

III. DIAGNOSIS STRATEGY

CLIPS expert system shell is used to accomplish the diagnosis tasks discussed in Section II [10]. The knowledge base consists of three sets of rules: rules for prediction of protection operation, rules for identification of unexpected protection operation, and rules for diagnosis of reasons for the symptoms.

A. Prediction of Protection Operation

In order to predict the statuses and timings of elements, forward chaining reasoning is employed to simulate the protection operation chain. Forward chaining reasoning is also called bottom-up reasoning. It reasons from lower level facts to top level conclusion [1]. The protection operation chain fits into this concept. The disturbance information, relay settings and performance specifications are lower level facts. Rules are written to simulate the transition of statuses of elements. The inferred statuses and corresponding timings, combined with relay settings and performance specifications are the inputs to the next transition. Thus, the whole protection operation chain can be simulated until the final conclusion is reached, which

reads as "Fault currents are interrupted by the circuit breaker at time T". Fig. 2 illustrates the forward chaining reasoning for prediction of protection operation, which only details the operation of phase distance elements.

B. Identification of Unexpected Protection Operation

Identification of unexpected protection operation is based on comparison of predicted statuses and timings of elements with the actual ones which are obtained from the relay event report and oscillography file.

The status comparison is based on the existence and non-existence of predicted status and actual status of an operand. The predicted status is regarded as a hypothesis and the actual status is regarded as a fact. If both the hypothesis and the fact exist, the correctness of the status is validated. If the hypothesis exists and the fact does not exist or the hypothesis does not exist but the fact exists, a symptom will be identified. For example, if the hypothesis "Current Interruption by Circuit Breaker" exists but there is no such a fact, the symptom "Circuit breaker should have interrupted currents but failed" will be identified.

The operating speed of protection elements and the associated circuit breaker is evaluated by examining the timing of operands. Fig. 3 shows the logic for evaluating the operating speed of protection elements. The logic for evaluating the operating speed of the circuit breaker is similar.

With the timing information of protection elements available, whether the relay trip is triggered by the expected protection element is also examined.

C. Diagnosis of Symptoms

As discussed in Section II, a symptom of unexpected status or timing may be caused by a malfunction of its directly related logic component or by a malfunction of logic components at lower level of protection operation chain due to
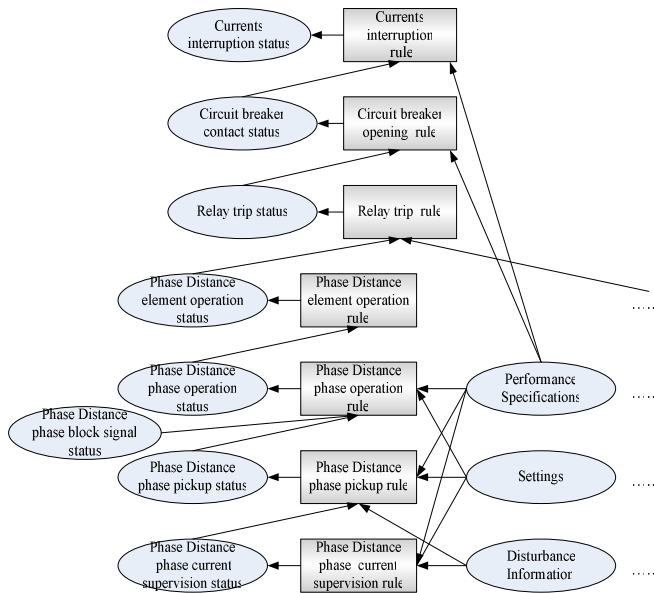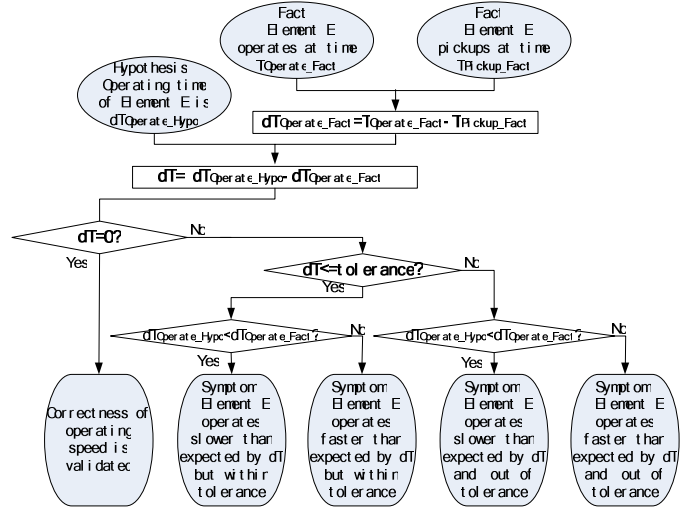
Fig. 3. Logic reasoning for evaluating operating speed of protection elements

the propagation of abnormalities. Backward chaining reasoning is employed to trace out the malfunctioned logic components.

Backward chaining reasoning is also called top-down reasoning. Along the reasoning chain, in order to prove higher level hypotheses, the intermediate hypotheses must be proven. Thus the reasoning will trace the basic facts to prove the hypotheses. This mechanism is quite suitable for a diagnosis problem [1].

In the context of our problem domain, the backward reasoning chain is defined in terms of a goal which can be accomplished by satisfying sub-goals. We use Fig. 4 and TABLE III to explain the reasoning process. Suppose the symptom "Circuit breaker currents interruption failed" is identified, finding the reason for this symptom will be set as the initial goal (Goal 1). Then the existence of the symptom "Circuit breaker failed to open" will be tested. If it does not exist, it proves that the contact signal indicated circuit breaker opening but in fact the circuit breaker did not interrupt the fault currents. Obviously the diagnosis will be "Circuit breaker malfunctioned". But if the symptom "Circuit breaker failed to open" exists, it proves that the circuit breaker failed to interrupt fault currents because the circuit breaker failed to open. A sub-goal (Goal 2) will be created to find the reason for the symptom "Circuit breaker failed to open". Following this pattern, the second or more sub-goals will be created and the malfunctioned logic components will be finally traced. It should be noticed that because the relay trip can be triggered by the operation of any enabled protection element, if the symptom "Relay failed to trip" is identified, sub-goals (Goal 4.1, Goal 4.2, ……) for diagnosis of operation of each enabled element may be created at the same time. Likewise, sub-goals (Goal 4.1.1, Goal 4.1.2, ……) may be created for diagnosis of operation of individual phase of an enabled protection element.

Another typical type of symptoms is "Relay trip should be triggered by the operation of X Element, but it was actually triggered by the operation of Y Element". The reason for this symptom could be the failure of operation of X or the fact that Y operates faster than expected and even faster than X. Therefore sub-goals for diagnosis of operation of X and diagnosis of operating speeding of Y will be created.
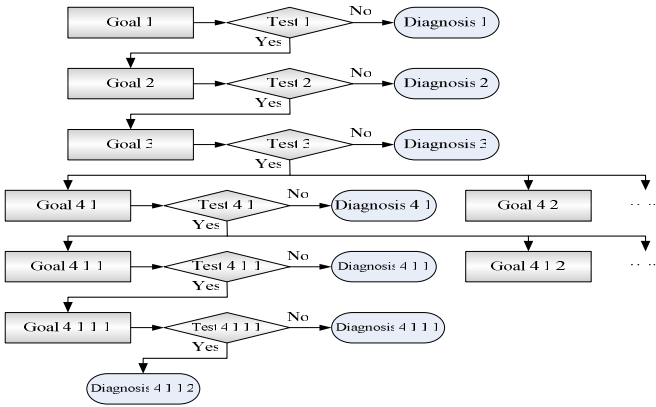
Fig. 2. Forward chaining reasoning for prediction of protection operation

Fig. 4. Backward chaining reasoning for diagnosis of symptoms

TABLE III
EXPLANATION OF BACKWARD REASONING PROCESS

Goal	
Goal 1	To find the reason for the symptom "Fault currents interruption failed"
Goal 2	To find the reason for the symptom "Circuit breaker failed to open"
Goal 3	To find the reason for the symptom "Relay failed to trip"
Goal 4.1	To find the reason for the symptom "Phase Distance Element (Zone 1, Zone 2, ……) failed to operate"
Goal 4.2	To find the reason for the symptom "Phase IOC Element failed to operate"
Goal 4.1.1	To find the reason for the symptom "Phase A-B of Phase Distance Element (Zone 1, Zone 2, ……) failed to operate"
Goal 4.1.2	To find the reason for the symptom "Phase B-C of Phase Distance Element (Zone 1, Zone 2, ……) failed to operate"
Goal 4.1.1.1	To find the reason for the symptom "Phase A-B of Phase Distance Element (Zone 1, Zone 2, ……) failed to pickup"
Goal 4.1.1.2	To find the reason for the symptom "Over-current supervision of Phase A-B of Phase Distance Element (Zone 1, Zone 2, ……) failed"
Test	
Test 1	Does the symptom "Circuit breaker failed to open" exist?
Test 2	Does the symptom "Relay failed to trip" exist?
Test 3	Does the symptom "All the protection elements expected to operate failed to operate" exist?
Test 4.1	Does the symptom "All the phases of Phase Distance Element (Zone 1, Zone 2, ……) expected to operate failed to operate" exist?
Test 4.1.1	Does the symptom "Phase A-B of Phase Distance Element (Zone 1, Zone 2, ……) failed to pickup" exist?
Test 4.1.1.1	Did the symptom "Over-current supervision of Phase A-B of Phase Distance Element (Zone 1, Zone 2, ……) failed" exist?
Diagnosis	
Diagnosis 1	Circuit breaker malfunctioned.
Diagnosis 2	Wire connection between the relay and the circuit breaker is broken.
Diagnosis 3	Logic component for Relay Trip malfunctioned.
Diagnosis 4.1	Logic component for Operation of Phase Distance Element (Zone 1, Zone 2, ……) malfunctioned.

Diagnosis 4.1.1	Logic component for Operation of Phase A-B of Phase Distance Element (Zone 1, Zone 2, ……) malfunctioned.
Diagnosis 4.1.1.1	Logic component for Pickup of Phase A-B of Phase Distance Element (Zone 1, Zone 2, ……) malfunctioned.
Diagnosis 4.1.1.2	Logic component for Over-current Supervision of Phase A-B of Phase Distance Element (Zone 1, Zone 2, ……) malfunctioned.

IV. SYSTEM IMPLEMENTATION

In our solution, CLIPS expert system shell is used to perform the major diagnosis analysis. In order to facilitate data inputs from relay files and reports, and data outputs to the diagnosis report, a windows framework is developed using Visual C++.

The inference engine of CLIPS expert system shell is linked with the framework by means of Dynamic Link Library (DLL). Besides the initial facts, the rules stored in a text file are also loaded into the inference engine from the windows framework. In this section, we will discuss the implementation of knowledge representation by CLIPS rules.

A. Forward Chaining Rules for Prediction of Protection Operation

The forward chaining rules for prediction of protection operation are constructed by simulation of transition from lower level to higher level of protection operation chain. The antecedent of a rule usually consists of patterns for disturbance information, settings and performance specifications and element status. The consequent of a rule is an action to assert a new element status. The following is an example in CLIPS code which predicts the pickup status and corresponding timing of Phase A of Phase IOC Element based on the disturbance information and relay settings.

```
(defrule Phase_IOC_Phase_A_Pickup
  (DisturbanceInformation (FaultType          A ? ? ?)
                          (FaultInceptionTime ?Inception))
  (IOCElementSetting      (ElementType        Phase IOC)
                          (Function           Enabled)
                          (PickupDelayTime    ?Pickup_Delay))
  =>
  (assert (ElementStatus  (FactType       Hypothesis)
                          (ElementType  Phase IOC)
                          (ElementPhase A)
                          (Status         Pickup)
                          (Timing         (+ ?Inception ?Pickup_Delay)))))
```

B. Rules for Identification of Unexpected Protection Operation

The antecedent of a rule for identification of unexpected element status consists of a pattern for the hypothesis status and a pattern for the fact status, one of which is qualified by the "not" condition element to represent the absence of the status. The consequent of the rule is an action to assert validation information or symptom information.

The rules for evaluation of operating speed of protection elements make use of the math functions and predicate functions of CLIPS language.

C. Backward Chaining Rules for Diagnosis of Symptoms

The backward chaining reasoning rules are not directly constructed because CLIPS is forward-reasoning-oriented and its inference engine does not directly support backward

reasoning mechanism. Thus backward chaining must be emulated using forward chaining rules. Our approach is to represent the cause-effect rules for protection operation chain as facts so that the antecedents and consequents can be examined by a set of rules which act as a backward chaining inference engine.

The following are examples of the cause-effect rules in CLIPS code.

```
(Rule (If    CB Open Failed)
      (Then CB Current_Interruption Failed))
(Rule (If    Relay Trip Failed)
      (Then CB Open  Failed))
(Rule (If    Phase_Distance_Zone2 Operation Failed and Phase_IOC
Operation Failed)
      (Then  Relay Trip Failed))
```

The backward chaining inference engine is implemented with two sets of rules. The first group generates sub-goals and diagnosis information based on the results of tests. The pseudo-code is as follows

If   the goal is "find the cause for E"
 and a rule " C may be one of the causes for E" exists
 and a symptom for C exists
Then a sub-goal "find the cause for C" is created

If   the goal is "find the cause for E"
 and a rule "C may be one of the causes for E" exists
 and no symptom for C exists
Then a diagnosis conclusion "the cause for E is the malfunction of the component directly related to E" is made

The following is the corresponding CLIPS code.

```
(defrule Engine_For_Generate_Sub-goal
    (Goal  (FindReasonFor ?Element_e ?Phase_e ?Status_e Failed))
    (Rule  (If    ?Element_c ?Phase_c ?Status_c Failed $?)
           (Then ?Element_e ?Phase_e ?Status_e Failed))
    (Symptom (Symptom  ?Element_c ?Phase_c ?Status_c Failed))
    =>
    (assert (Goal (FindReasonFor ?Element_c ?Phase_c ?Status_c Failed))))

(defrule Engine_For_Generate_Diagnosis
    (Goal  (FindReasonFor ?Element_e ?Phase_e ?Status_e Failed))
    (Rule  (If    ?Element_c ?Phase_c ?Status_c Failed $?)
           (Then ?Element_e ?Phase_e ?Status_e Failed))
    (not (Symptom (Symptom ?Element_c ?Phase_c ?Status_c Failed)))
    =>
    (assert  (Diagnosis (Symptom ?Element_e ?Phase_e ?Status_e Failed)
                        (Reason  ?Element_e  ?Phase_e  ?Status_e
Component Malfunctioned))))
```

The second group of rules performs update operation to modify the cause-effect rules to eliminate the condition which has been satisfied.

V. EXAMPLE

In this section we use a simplified example to demonstrate the capability of the expert system. The system will analyze a set of files and reports generated by a relay and produce the diagnosis report.

ATP program is used to simulate the disturbance event. Commercial software called RELAY ASSISTANT and a relay test set are used to generate the simulated voltage and current signals to trigger the relay operation [11]. Contact signals of

the circuit breaker associated with the relay are simulated using programmable logic operands and timers inside the relay. The timings of contact signals are set to match the event simulated in ATP program. The disturbance information is shown in TABLE IV.

Phase IOC Element, Ground IOC Element, and Phase Distance Element and Ground Distance Element for Zone 1 and Zone 2 operation are enabled. The relay and associated circuit breaker should respond to the fault according to settings and performance specifications. Phase Distance Zone 2 Element and Ground Distance Zone 2 Element of the relay are expected to operate to make the relay trip at 0.522 second and the circuit breaker currents are expected to be interrupted at 0.586 second.

TABLE IV
DISTURBANCE INFORMATION

Fault Type	A-B-G
Fault Location	Zone 2
Fault Inception Time	0.200 second
CB Currents Interruption	Succeeded
CB Currents Interruption Time	0.784 second

The actual behavior of the relay and the circuit breaker in terms of statuses and timings of logic operands are recorded in the event report. In order to demonstrate the analysis capability of the system comprehensively, we have deliberately manipulated the event report to introduce some abnormities.

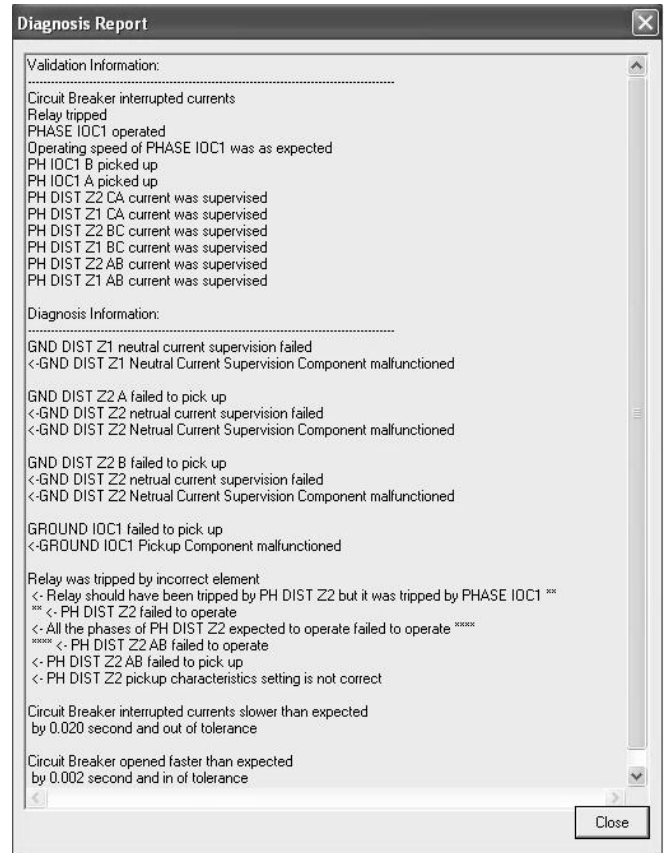Diagnosis results are shown in Fig. 5. It includes both the

Fig. 5. Validation and diagnosis report

validation information and diagnosis information. The validation information section lists the logic operands whose

status is as expected and the protection elements whose operating speed is as expected.

As shown in the validation information section, PHASE IOC Element operated to make the relay trip. The circuit breaker opened because of the relay trip and the fault currents were interrupted by the circuit breaker.

Several abnormities were identified and diagnosed as shown in the diagnosis information section. Ground Distance Zone 2 Element should have picked up but failed to pick up because its neutral current supervision failed. The neutral current supervision of Ground Distance Zone 1 Element also failed. In addition, Ground IOC Element failed to pick up. From the diagnosis information for ground elements, we may know that it is highly possible that something is wrong with the neutral current channel.

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 longer than that of Phase Distance Zone 2 Element, the relay trip and circuit breaker currents interruption was delayed. That is the reason why the circuit breaker currents should have been interrupted at 0.586 second but it actually happened at 0.784 second.

The reason for failure of operation of Phase Distance Zone 2 Element was that the pickup characteristics setting for Phase Distance Zone 2 Element was not correct.

There was also timing diagnosis information related to circuit breaker. The circuit breaker opened a little bit faster than expected but within pre-set tolerance. However, it interrupted currents slower than expected. The delay was out of the pre-set tolerance.

All the validation and diagnosis information is as expected, which proves the correctness of the diagnosis analysis.

VI. CONCLUSIONS

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

1) Files and reports generated by digital relays contain abundant information 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.

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

4) Backward chaining reasoning can be implemented in an expert system shell designed with forward chaining reasoning mechanism by emulating backward chaining inference engine. This makes the forward-chaining-oriented expert system shell more flexible.

Some future work is proposed. First, the knowledge base may be expanded to make the expert system applicable to more types of relays. Second, the disturbance information essential for analysis is supposed to come from other fault analysis applications based on advanced algorithms and techniques. It is desirable to integrate one or more of these applications with this expert system to achieve a comprehensive fault analysis application.

VII. REFERENCES

[1] J. Giarratano, G. Riley, *Expert Systems Principles and Programming*, PWS Publishing Company, Boston, 1994

[2] Working Group D10 of the Line Protection Subcommittee, Power System Relaying Committee, "Potential applications of expert systems to power system protection", *IEEE Trans. Power Delivery*, vol. 9, no. 2, pp. 720- 728, April 1994

[3] Y. Sun, C. C. Liu, "RETEX (RElay Testing EXpert): an expert system for analysis of relay testing data", *IEEE Trans. Power Delivery*, vol. 7, no. 2, pp. 986-994, April 1992

[4] M. Kezunovic, P. Spasojevic, C. Fromen, D. Sevcik, "An expert system for transmission substation event analysis", *IEEE Trans. Power Delivery*, vol. 8, no. 4, pp. 1942-1949, October 1993

[5] S. D. J. McArthur, J. R. McDonald, S. C. Bell, "Expert systems and model based reasoning for protection performance analysis", *Artificial Intelligence Applications in Power Systems, IEE Colloquium on*, April 20, 1995

[6] D. Costello, "Understanding and analyzing event report information", technical paper, Schweitzer Engineering Laboratories, Inc., Pullman, WA, 2000, http://www.selinc.com/techpprs.htm

[7] *Instruction Manual for D60 Line Distance Relay*, General Electric Company, Fairfield, CT, 2004

[8] S. Vasilic, M. Kezunovic, "An improved neural network algorithm for classifying the transmission line faults", IEEE PES Winter Meeting, New York, Jan 2002.

[9] M. Kezunovic, B. Perunicic, "Automated transmission line fault analysis using synchronized sampling at two ends", *IEEE Trans. Power Systems*, vol. 11, no. 1, pp. 441-447, February 1996

[10] J. C. Giarratano, *CLIPS User's Guide, Version 6.20*, NASA Lyndon B. Johnson Space Center, Houston, TX, 2002

[11] *Primer for PC-Based Simulator for Relay Testing*, Test Laboratories International, Inc., College Station, TX, 2002, http://www.tli-inc.com.

VIII. BIOGRAPHIES

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