An Expert System for Automated Analysis of Circuit Breaker Operations

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***Abstract*-- An expert system for automated analysis of circuit breaker operations is introduced. This advanced system enhances the on-line circuit breaker condition monitoring by providing consistent rule-based analysis and quick diagnosis for different types of circuit breakers. The paper describes circuit breaker operation background, the implementation of the data pre-processing and expert system, and provides an overall solution that demonstrates the entire process. This expert system has been tested by the data collected from a utility company.**

***Index Terms*-- Circuit Breaker, Monitoring, Signal Processing, Expert System, Automated Analysis, Feature Extraction**

I. Introduction

Circuit breaker (CB) in a power system usually has a lifetime of about 20 to 40 years. In most of its lifetime CB remains closed and occasionally it is called upon to interrupt load and fault current. Some parts of breaker will wear out due to operations. For instance, the contact material will erode due to the arcing generated when the contact opens. Some parts of breaker will deteriorate due to its inertia. For instance, the increased friction of the mechanical parts may be caused by lack of proper lubrication. Gradually, these conditions may develop into failures that will prevent CB from performing its functions.

During breaker's service time, maintenance and inspection are imperative duties to detect early symptom of a failure. The main concern of a utility company is to reduce the maintenance cost without sacrificing the reliability of CB operations since a major failure of CB may incur significant replacement cost and customer outages. Condition monitoring becomes a widely accepted strategy to solve this problem.

With technology development in data acquisition and communication area, it is not difficult to develop a condition monitoring system for CB [1]. However, the original data being monitored and recorded by the system is usually hard to interpret [2]. The experience with condition monitoring system from a utility company tells that the analysis of data heavily depends on an individual judgment, and any false conclusion may lead to no or incorrect maintenance action. Furthermore, the profile of monitoring data depends upon the type of CB, working condition and time interval since CB placed service. The data are changing gradually with the increase of CB operations, which increases the difficulty in analyzing it.

The paper proposes an expert system based automated analysis solution. The first section gives the background of CB operation and monitoring data. It is followed by a discussion of the subsystems for feature extraction and expert system analysis. An overall expert system solution is discussed next. Its performance is demonstrated through the data collected from different types of CB. Conclusions and references are given at the end.

II. BACKGROUND

CBs of various types from different manufacturers vary greatly in their mechanical and electrical design. One uniform method to monitor CBs of different types is to monitor the control circuit of CB [1]. The control circuit can be simplified as shown in Fig. 1. It may be divided into several sub-systems; trip and close are two major ones. The heater (H) and motor (M) are also included in Fig. 1.

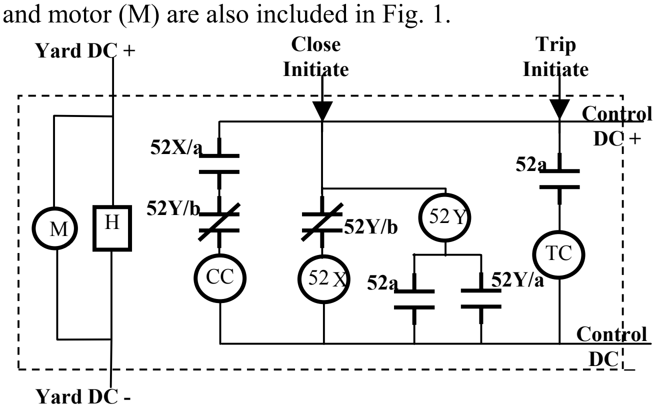

Fig. 1. Circuit Breaker Control Circuit

The signals (both voltages & currents) collected from

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control circuit are called performance indicators or "CB signatures". Table 1 provides a list of the signal names. "Supply DC" provides voltage to both the trip and close subsystem, and yard dc provides voltage to the motor (M) or heater (H). The dc voltage comes from the substation batteries. Loss of battery voltage or power or other problems with the batteries may directly affect the control circuit, and consequently, CB may not be able to operate.

TABLE 1 SIGNALS FROM A CONTROL CIRCUIT OF A CIRCUIT BREAKER

OPEN OPERATION	CLOSE OPERATION
TRIP INITIATE	CLOSE INITIATE
SUPPLY DC VOLTAGE	SUPPLY DC VOLTAGE
YARD DC VOLTAGE	YARD DC VOLTAGE
A CONTACT	A CONTACT
B CONTACT	B CONTACT
TRIP COIL CURRENT	CLOSE COIL CURRENT
PHASE CURRENTS	PHASE CURRENTS
	X COIL
	Y COIL

Coming from an operator in the control house, SCADA, relay, or other source, the initiate signal is sent to CB to start its operation. The initiate signal transition from OFF to ON indicates the start of the CB operation. Loss of the initiate signals indicates a major problem in the sequence of relay operation.

Trip and close coil currents (TC and CC in Fig. 1) are used to energize the trip and close coil respectively. Each trip and close coil activates a plunger that causes the operating mechanism to operate. When the trip or close coil is energized, the electric-magnetic force on the plunger initiates the movements of the whole mechanism. The movements of operating mechanism can be reflected in the coil currents through the electric-magnetic effect. Depending upon the mechanical and electrical nature of CB, the current takes different waveforms. In fact, monitoring of coil currents provides insights into the condition of both the coil and operating mechanism.

A and B contacts signals (52a and 52b) indicate the voltage across auxiliary switches, which signify the open or close status of CB. They are designed such that there is always a time difference between changing of "A contact" and "B contact". The reciprocal of that time difference is proportional to the velocity of CB operation. Any deformation of the signal may indicate a dirty contact, a binding mechanism, or a slow breaker, etc.

Phase currents of the CB are acquired in addition to the signal collected from the control circuit. They provide additional information that can be used to check the reliability of the status of signals from the control circuit. Any inconsistency may indicate a wrong cable connection or a problem with the operating mechanism. If phase currents show that CB operated correctly, but one of the contacts is not sensing the correct status of CB, then one can conclude that there is a problem with the contact or operating mechanism.

Y coil (52Y) are used to prevent multiple-close attempts in a close operation [2].

III. FEATURE EXTRACTION

An expert takes a look at newly recorded data, compares it with old records, and draws a conclusion based on the overall information. However, an automated analysis system works differently. In order to catch information from the original data, it must be able to describe the information quantitatively. A feature is a piece of information that needs to be and can be quantified. A signal parameter is used to quantify the feature.

A. Feature Definitions

The important features for the CB condition analysis fall into two categories: Sequence of Events and Quality of Individual Signals. Events refer to a state transition or an unusual change in the waveform profile. The time when the events happen and sequence of events are of interest for analyzing the CB condition. A maximum of ten events have been identified in Table 2. Not all of these events will take place in a CB operation. For example, events related to X and Y coil will only appear in a close operation for certain types of CB. The first seven events are expected to show up in every data record as indicated in Fig. 2.

TABLE 2 EVENTS DEFINITION FOR CB PERFORMANCE INDICATORS

Event #	Event Description	Time
1	Trip or close operation is initiated. (Trip or Close initiate signal change from low to high)	T1
2	Coil current picks up	T2
3	Coil current dips after saturation	T3
4	Coil current begins to drop	T4
5	B contact breaks or makes (a change of status from low to high or from high to low)	T5
6	A contact breaks or makes	T6
7	Phase currents breaks or makes	T7
8	X coil current picks up	T8
9	X coil current drops out	T9
10	Y coil current picks up	T10

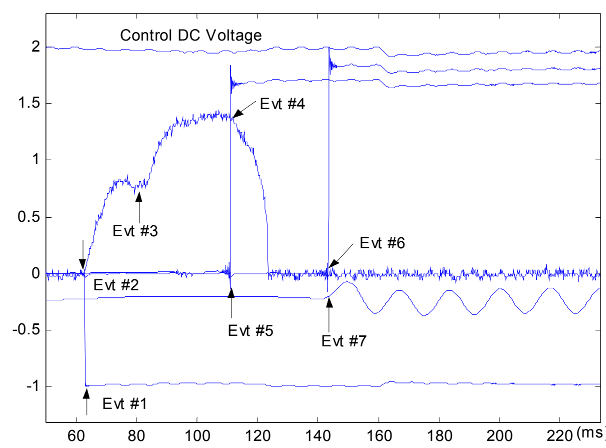

Fig. 2. Sequence of events features for a CB close operation

All events are required to take place around the expected time, and some events also have to conform to the following requirements:

1. $T2 - T1 < S$ (S is the expected value)
2. Free Travel Time = $|T3 - T2 - S| < \varepsilon$ (S is the expected travel time)

3. Mechanism Travel Time = T5 – T3 – S < ε (Close operation, S is the expected mechanism travel time)
4. Mechanism Travel Time = T6 – T3 – S < ε (Trip operation)
5. T5 < T4 < T6 (Close Operation)
6. T6 < T4 < T5 (Open Operation)
7. $\|T5 - T6| - S| < \varepsilon$
8. $\max\left(T_{pA}, T_{pB}, T_{pC}\right) - \min\left(T_{pA}, T_{pB}, T_{pC}\right) < S$
9. T10 < T9

Signals are not always as "clean" as shown in Fig. 2. Coil currents may be loaded with heavy noise that makes it hard to find where the dip is located. The energized coil current may appear choppy. There might be a spike, ripple or distortion observed on the dc voltage. Even a contact signal may be distorted with noise or bounce. These abnormal behaviors describing the quality of individual signals are yet helpful in telling the condition of certain parts of CB. Signal parameters such as SPI (spike), NOI (noise), RIP (ripple), etc, are defined to carry the features for certain signal together with all the time parameters from Table 2.

B. *Feature Extraction*

The local information (e.g. an event) mingled with global features (e.g. ripples) makes the wavelet decomposition and reconstruction filter banks a perfect feature extractor for this data pre-processing application [3]. During the pre-processing, it is necessary to perform a three-level feature extraction: de-noising, splitting and signal parameter calculation.

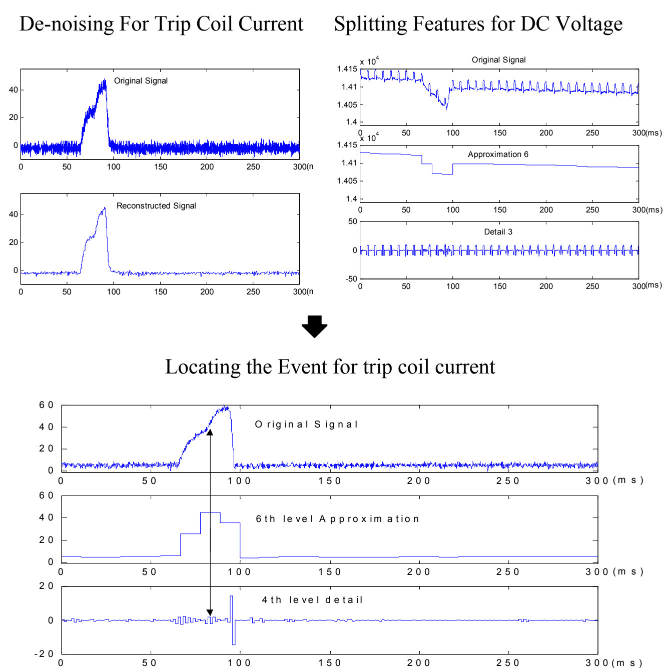

Fig. 3. Three level features extraction

De-noising is used to suppress the excessive instrumentation noise and reveal the features that may be distorted by the noise. Soft thresholding is used in de-noising to preserve the desired signal features. As the de-noising example shown in Fig. 3, the reconstructed trip coil current beneath the noisy one still contains the dip feature.

The Splitting process is expected to separate the features to facilitate the calculation of the signal parameters for individual features. In the splitting example shown in Fig. 3, "Supply DC" voltage is decomposed into six levels using "db1". Signal approximation at level 6 contains the general profile and the detailed signal at level 3 catches the ripple feature.

Signal parameters are calculated after de-noising and splitting process. The event location example in Fig. 3 shows how to detect the dip event in the trip coil current. The 6th level current approximation takes the shape in steps. The 4th level detail preserves all the event information such as the beginning time, the dip time and the de-energizing time of the coil current. Making a correlation between the approximation and detail signal helps to locate the dip time within the significant stair.

IV. Expert System

Further analysis of CB operation is performed by a rule-based expert system. The purpose of developing an expert system was to emulate the decision-making process of a human expert [4]. The system was designed and developed through extensive interviews with a group of experts at CenterPoint Energy. The interviews enabled the designers to incorporate human expertise into an expert system that could emulate the reasoning of experts. By preserving knowledge in an expert system, it ensures that the analysis of all future recordings will be performed in a consistent manner.

A. *Expert System Implementation*

The developed expert system mainly consists of a CLIPs DLL, a rule file and a setting file [5]. CLIPs DLL implements the expert system engine. Both rule file and setting file are facts of the expert system. The rule file contains all the expert system rules designed for this special application. The setting file is compressed into special format. The source code written in C++ reads the settings into the memory and sends it into the expert system engine (CLIPs DLL) together with the signal parameters. The rule file is loaded directly into the engine. After analysis, the inference engine generates a final report about the CB operation condition. Both facts and reports are accessible through user interface as shown in Fig. 4.

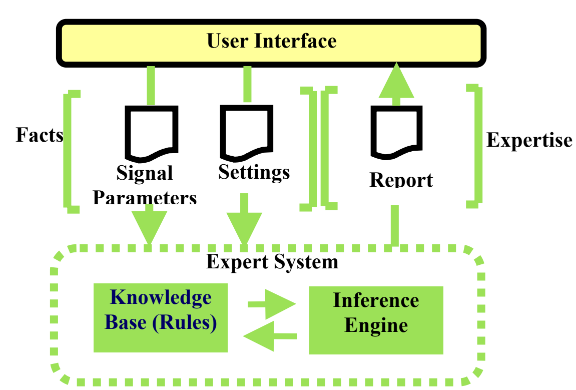

Fig. 4. Expert system analysis process

B. Rule Based Knowledge Representation

The developed knowledge base contains three types of rules: basic, complex and output rules. Basic rules are fired directly by signal parameters. They are used to make sure that all the extracted parameters are within their corresponding tolerances. If a parameter is outside a tolerance, then the rule that checks the parameter becomes activated. The activated rules from the first layer of analysis provide some preliminary results about the CB condition. Complex rules can be fired by signal parameters either directly or indirectly through other rules. They are used to analyze the interrelationship between all of the activated basic rules. Based on which rules were activated, the expert system tries to come to a conclusion about the overall performance of CB. A certain combination of basic rules may indicate a particular problem whereas a different combination would indicate another problem. The output rules are responsible for printing out proper maintenance and inspection instructions based on a conclusion about the CB operation [6].

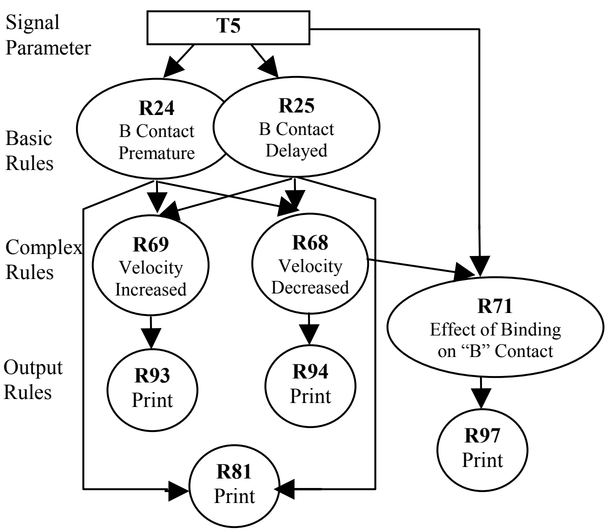

Fig. 5. Layers of Analysis

The inference engine uses the forward chaining method. Usually a basic rule is fired by certain signal parameters at the beginning, which may fire more complex rules in a way similar to a chain reaction. Each inference thread ends with an output rule. Fig. 5 illustrates the expert system rules and the inference process. The rectangle represents the signal parameter T5 mentioned in Table 2. The two ovals right below it represent the basic rules that can be fired by T5. The three ovals named R69, R68 and R71 represent the complex rules that can be fired directly or indirectly by T5. The remaining ovals represent output rules.

Basic rules 24 and 25 are created to verify that the "B" contact signal does not make premature or delayed transition to its sustained value. Rule 24 will be fired if the "B" contact voltage makes transition to its sustained value before the expected time instant, which equals to a difference between the set value and its tolerance. Rule 25 will be fired if the "B" contact voltage makes transition to its sustained value after the expected time instant, which equals to a sum of the set value and its tolerance.

Complex rules 68 and 69 are created to verity the velocity of the breaker mechanism movement. R68 will be fired if the time difference between "A" and "B" contact transitions is increased and vice versa, R69 will be fired if the time difference is decreased. Suppose "A" Contact is normal in a CB open operation. The fact that "B" contact is delayed fires R25. As shown in Fig. 6, R68 is fired in this case.

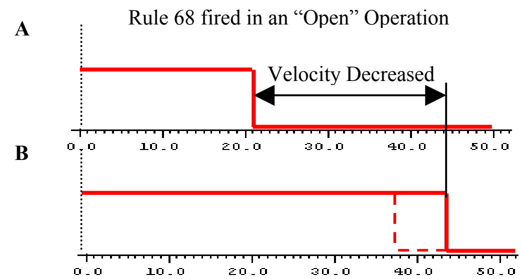

Fig. 6. Rule 68 fired in an CB "Open" Operation

Complex rule 71 (Fig. 7) verifies that the movement of the "B" contact occurs without an increased bearing friction. It will be fired if the T5 is normal and the velocity is decreased due to the delayed or premature change of "A" contact.

In summary, CB condition analysis demands a wide range of information and yet different combinations of the information may lead to different analysis result. Because of the nature of this application, the knowledge base consists of 60% basic rules and 15% complex rules.

```
;----Effect of Binding on "B" Contact----
;
(defrule R71
   (declare (salience -900))
   (initial-fact)
   (not (R71_fired))
   (closing)
   (b_contact ?TIM ? ? ?)
   (set_b_contact ?SETTIM ?TOL ? ?)
   (R68_fired)
   (test (< ?TIM (+ ?SETTIM ?TOL)))
   (test (> ?TIM (- ?SETTIM ?TOL)))
=>
   (assert (R71_fired))
   (printout t crlf  " R71: Effect of mechanism binding (bearing friction) on
'B' contact!" crlf)
   (printout outFile crlf " R71: Effect of mechanism binding (bearing
friction) on 'B' contact!" crlf)
)
```

Fig. 7. Complex Rule for Effect of Binding on "B" Contact

V. Overall Solution

Fig. 8 displays architecture of the CB Monitoring software solution. Overall solution is divided on two parts: client and server side.

On the client side, digital fault recorder (DFR) collects data from the circuit breaker. Analysis software performs the processing using advanced signal processing and expert system methods. It gives to the field operator instant results about tested breaker performances and directions how to repair possible problems.

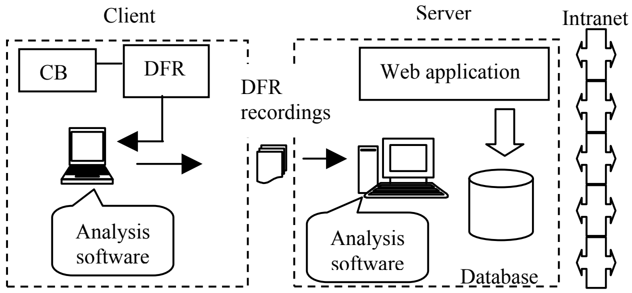

Fig. 8. System Architecture of the CB Monitoring System

On the server side, DFR records stemming from the breakers from the entire system are reanalyzed and together with the analysis results stored to the database. Data from the database are available to the users connected to the corporate network, which can search for the information using web browser software. Web application is developed using ASP.NET technology and C# programming language [7]. Web application together with the web server, processes the user's HTTP requests for the DFR records matching multiple criteria: time, date, place, breaker type, breaker operation etc. Using Structured Query language (SQL), web application parses the database and retrieves appropriate information. Attained data are embedded in HTML web pages, which are sent to the users across the TCP/IP network.

Figure 7 shows the structure of the analysis software. DFR records in COMTRADE file format are initially processed by the signal processing module (SP)[8][9]. It extracts the relevant signal parameters using predefined set of settings.

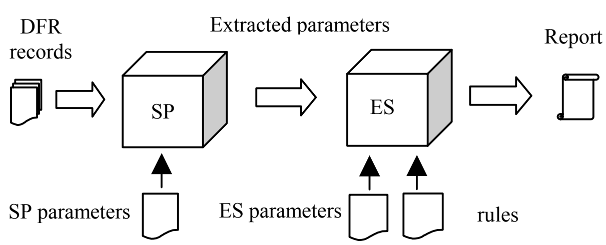

Fig. 9. Structure of the analysis software

Extracted parameters are sent to the expert system that emulates the reasoning of human experts using set of expert system parameters and rules. Both SP and ES parameters are customized for every particular type of breaker. After completion of the ES processing, final results are displayed in the form of a analysis report. Report contains information about CB performances in form of a list of fired rules. Reports can be saved to ASCII files, printed and/or saved to the database.

CB Monitoring enables data integration of DFR recordings originating from various DFR recorders. It utilizes standardized COMTRADE file format widely accepted by most DFR manufacturers.

IEEE file naming convention is used for naming processed DFR recordings files and reports [10]. Proposed convention defines schema for naming files containing time sequence data. File name compliant with the convention contains unique information about event: date, time, substation, company, breaker type and manufacturer, identification number etc. By using IEEE file naming convention, handling of large volumes of the record files is significantly simplified.

In Fig. 8, GUI of the analysis software is displayed. Windows labeled with (1) displays waveforms of the analyzed recording. With (2) are denoted signal names and corresponding extracted parameters. When the processing of the single DFR record is finished, analysis report is shown in modeless window labeled with (3).

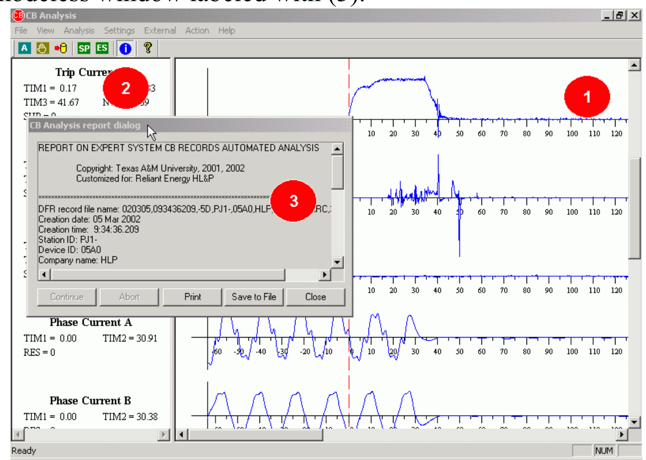

Fig. 10. Screenshot of the analysis software main window

VI. TEST RESULTS

Over the course of several months, CenterPoint Energy collected and provided a set of test cases from different types of CB. Test case is a COMTRADE format file that contains samples of all of the signals with unknown features. Expert system rules and facts including settings are fully developed before the testing. After the automated analysis of each record, the output was checked against the corresponding input file to verify that what are detected was indeed the features in the data. Table 3 provides an expert system report example with the comparison to the original features of a Westinghouse R3 breaker operation. The first part of the expert system report lists all the basic and complex rules fired by the case and the second part of the report are generated by the output rules.

The tests revealed several expert system decision-making sensitivities. The expert system can only detect and classify features that it was designed to analyze. If there are other features in the data, then the system will simply not recognize them. Extra development effort would be required for the system to be able to detect and classify new features.

The expert system decisions are also very sensitive to CB types. Different CB types are configured by different settings while the expert system rules remain untouched. Incorrect settings can cause the system to be oversensitive and detect everything as an abnormality or be under sensitive and not detect anything.

TABLE 3 TEST RESULT EXAMPLE

Test Case # 13	
Feature	Control voltage spike
	'A' contact noise
	'A' contact delayed
	X Coil deactivation delayed
	Y Coil activation delayed
	Velocity decreased
	Effect of mechanism binding (bearing friction) on 'B' contact
Expert System Report	-------------Expert System Log--------------
	The record indicates a closing operation!
	R2: Breaker closes!
	R10: Control voltage spike!
	R16: 'A' contact noise!
	R19: 'A' contact delayed!
	R55: X Coil deactivation delayed!
	R59: Y Coil activation delayed!
	R68: Velocity decreased!
	R71: Effect of mechanism binding (bearing friction) on 'B' contact!
	------Maintenance & Repair Information------
	Check substation battery, charging system, and control cables.
	Check auxiliary assembly, contacts, and linkage.
	Check close circuit connections.
	This breaker is slow. The auxiliary alignment needs to be checked.
	An auxiliary contact may be broken or the mechanism may be binding.

VII. CONCLUSIONS

This expert system application improves CB operation analysis by automating the analysis process, accelerating the analysis speed, providing consistent analysis calibrations, allowing compatibility with different CB types, and enabling user-friendly access to CB operation records.

VIII. ACKNOWLEDGMENT

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X. BIOGRAPHIES

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