AUTOMATED ANALYSIS OF CIRCUIT BREAKER OPERATIONS

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ABSTRACT

The automated circuit breaker diagnostic system described in this paper is an extension of the widely used portable circuit breaker testing device concept. These traditional testing devices can be connected to the circuit breaker's control circuit to record analog and digital signals. The operator opens and closes the circuit breaker each time the test is performed and makes the recordings. The traditional analysis is done manually by overlaying traces from a "good" case recorded earlier and making a judgment of how different the new case is.

The new solution automatically performs the analysis. The automated system software consists of a signal processing module and an expert system module. The two modules process the voltage and current signals recorded by the test device and diagnose and report any abnormalities that are discovered. The paper describes the system requirements, the implementation of the two system modules, and provides an example that demonstrates the entire analysis process. Real data recorded in a substation has been used to test the system.

The system is packaged as a client/server application. The client part resides on a laptop and is carried out to the field by the maintenance crew. It allows for the recorded files to be downloaded and imported in to the software. The client application can perform the analysis on-site. The other option is to import the recorded files into the server application that consists of the analysis modules, a database and a viewer. The database allows easy archiving and retrieving of all the records and related analysis reports. The viewer is implemented using a standard Internet browser tool. This implementation allows a search of the records and/or reports to be made from anywhere on the corporate network (intranet).

This solution facilitates the analysis process by providing timely results that are consistent, irrespective of who runs the analysis. The archiving and retrieving functions are quite convenient for easy access to the historical data, report generation and dissemination across the company.

I. INTRODUCTION

Condition monitoring idea and its application is gaining attention as a circuit breaker maintenance choice. Noteworthy efforts are devoted to developments of related techniques and devices, which is a prerequisite for a condition monitoring system [1][2][3]. Real experience with such development from a utility company shows the improvements in routine maintenance and inspection given that staffs are properly trained [4].

The utilization of the technology for automated analysis of circuit breaker operation has not been fully incorporated into the everyday maintenance procedure yet. Large number of circuit breakers under monitoring, lack of expertise in advanced data analysis, lack of data repository to provide useful statistical results and lack of decision-making tools may all contribute to this situation. The automated circuit breaker diagnostic system introduced here provides a solution customized for a portable circuit breaker testing device. The objective of the system is to combine techniques such as signal processing, expert system, database, and to generate a maintenance decision-support tool. It is envisioned that with further refinement, this system will eventually be used to support the everyday maintenance decision process.

II. SYSTEM FUNCTIONAL DESCRIPTION

The automated analysis process starts with the collected raw data and ends with a concise event report. It is assumed that data format is known and data acquisition system is developed to read the data into the new software. The developed system is capable of reading the circuit breaker operation signatures (called performance indicators [5]) in IEEE COMTRADE binary data format that stores sample of each signal in a data file as well as the channel information in a configuration file. Through the experience gained with this system, three major functions are identified.

Data Pre-Processing

Drawing conclusions regarding the operation of circuit breaker requires thorough analysis. Such analysis can never be performed directly on signal samples. Rather, the analysis is performed based on some characteristic parameters (features) of the recorded signals. A feature could be an event locating where the coil current picks up or when the phase currents breaks. A feature could also be an indictor of excessive noise when contact makes transition or a measure of voltage drop for the supply dc voltage. Signal parameters are used to describe the features quantitatively.

The choice and accuracy of calculation of characteristic signal parameters profoundly affect the results of the analysis. The choice of advanced processing tools is important as well. Some of the processing tools that are used for parameter extraction include Wavelet analysis, Fourier analysis, and digital filtering [6].

- Wavelet Analysis: Its ability for time-frequency localization corresponds very well to the type of signal processing that needs to be performed. The Wavelet decomposition and reconstruction algorithm is used in denoising and separating the signal features.
- Fourier Analysis: Fourier analysis is a classical tool in signal processing and analysis. Its use is related to obtaining information on frequency spectrum of the signal.
- Filtering: Digital filters are used to remove or extract certain signal components of the frequency spectrum. Common use of filters is to eliminate measurement noise.

Data Analysis

The core analysis is performed by an expert system emulating the reasoning of a human expert. This process incorporates overlaying a given record onto a reference record to establish or verify the existence of a discrepancy.

- Classification: the event needs to be classified i.e. recognized either as a closing or opening the breaker.
- Characterization: each signal describing the event needs to be characterized by finding its pertaining temporal information.
- Verifying signals: each signal describing the event needs to be analyzed based on the rules defined by the system designer and/or by the user. The purpose of this analysis is to verify that the features of each signal correspond to the ones normally expected. Common features will be recognized and reported.
- Verifying the cause-effect relationship among signals: the relationships involving multiple parameters and possibly multiple signals need to be analyzed to determine causes of observed signal features.
- Verifying operation: overall correctness of the breaker operation needs to be verified by comparing the actual breaker operation against the stored pattern(s) specified by the user. The pattern(s) is stored as settings, and the settings vary for different breaker types.
- Creating event reports: At the end of analysis, the system needs to create an event report in the form of a text file. Event report needs to clearly describe the object (circuit breaker), the event (operation) and the conclusions (performance).

Data Storing and Retrieving

The raw data, output results and settings of the system need to be stored in the database for future retrieving.

- Storing the raw data, event reports and settings: The software should be able to archive generated reports, raw data and settings. Both local and remote (network) archiving locations are provided.
- Retrieving Raw Data: Single record or multiple records can be selected from the database through criteria such as substation, breaker type, device number, breaker id, date, time or combination of different criteria. Waveform signature(s) can be shown individually or overlaid together for comparison.
- Retrieving Event Reports: Event report can be retrieved together with the raw data to facilitate the comparing between the waveform signatures and analysis results.
- Retrieving Settings: Settings for different breaker types can be reviewed, revised or created.

III. ANALYSIS PROCESS

General Discussion

The general discussion of the analysis process covers the data pre-processing and data analysis functions mentioned above. For the data pre-processing part, algorithms are designed to extract signal parameters that characterize the event features listed in Table 3 and other features listed in Table 4. For the data analysis part, expert system rules are defined to verify individual signal, to verify the relationship among multiple signals and to verify the overall correctness of the operation. The whole process is summarized in Figure 1. The rectangles represent the signal parameters and the ovals represent the expert system rules.

Both signal parameters and settings (stored patterns) are loaded initially to the expert system as established "facts" [6]. The settings are ignored in Figure 1. The basic rule layer uses the monitored signal names as representatives of a group of basic rules belonging to that signal. For instance, 12 rules have been defined for A and B contacts including contact flat, premature, delayed, bounce, noise, unstable, etc. The set of basic rules compare the signal parameters with the settings to make sure that all the extracted parameters are within their corresponding tolerances. If a parameter is outside a tolerance, the rule that checks the parameter becomes activated, which establishes a new "fact": rule x has been fired.

Signal Parameters

NOI, BOU, DIP / T5, T6

RIP, DIS, SPI, DIP

DRP / T1

RES / T7

DRP / T8, T9, T10

NOI, SUP / T2, T3, T4

Basic Rules

A & B Contact

DC Voltages

Phase Currents

X & Y Coils

Trip & Close Initiates

Coil Currents

Complex Rules

Stuck Breaker

Trip Latch Friction

Velocity Decreased

Trip Latch Maladiustment

Slow Breaker

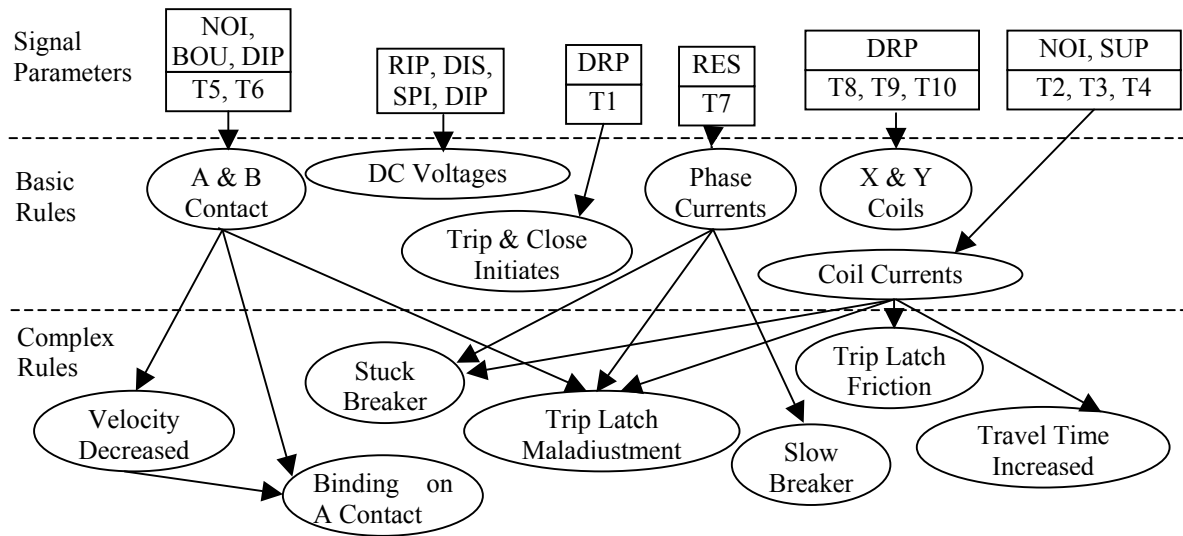Travel Time Increased

Binding on A Contact

Figure 1
Layers of Analysis

The basic rules either provide some preliminary "facts" about the circuit breaker condition or provide final evaluation limited to certain part of a circuit breaker. As is, the expert system rules for "DC Voltage" shown in Figure 1, do not have further correlation with other rules. The "facts" established by the "DC Voltage" rules can tell the condition of the substation dc battery.

The complex rules analyze the signals interrelationship from all of the "facts" established by signal parameters and basic rules. Based on which rules were activated before, the expert system tries to come to a conclusion about the overall performance of the breaker. A certain combination of basic rules may indicate a particular problem whereas a different combination would indicate another problem.

The analysis results of each layer are logged to an expert system event report. The report provides useful information about the circuit breaker operation and makes suggestions to the maintenance personnel as where to look for the problem.

Event Report

The waveform signatures of a slow breaker are provided together with a reference operation in. The dotted lines indicate the expected features of a normal operation while the solid lines denote the actual features of this record. The event report in catches the normal and problematic features in the signals.
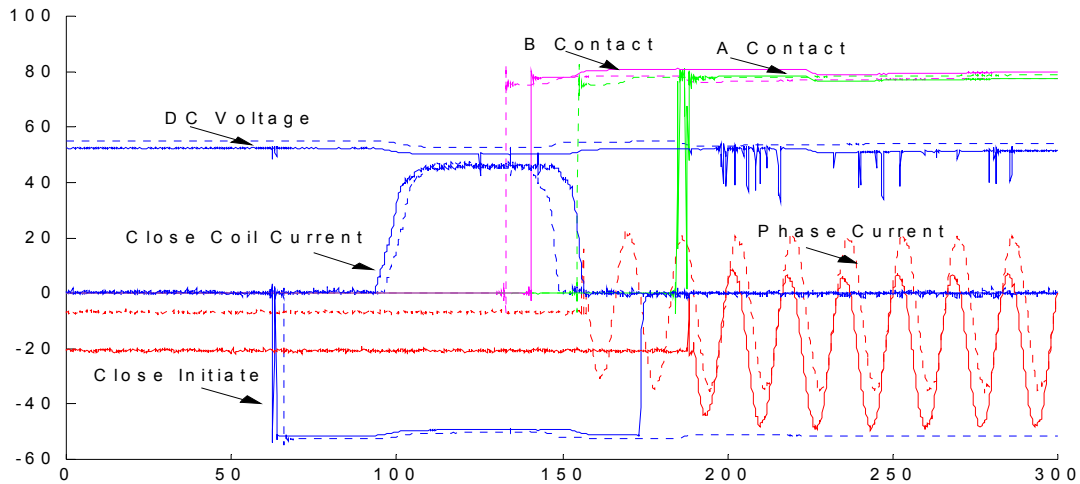
Figure 2
Slow Breaker Example: Waveform Signatures Compared with a Reference Case

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-------------Expert System Log--------------
The record indicates a closing operation!


R2: Breaker closes!
R7:  Control voltage unstable!
R19: 'A' contact delayed!
R25: 'B' contact delayed!
R35: Close coil current drop delayed!
R43: Phase A Current transition delayed!
R46: Phase B Current transition delayed!
R49: Phase C Current transition delayed!
R65: Slow breaker closing!
R68: Velocity decreased!


------Maintenance & Repair Information------
 Check substation battery, charging system, and control cables.
 This breaker is slow. The auxiliary alignment needs to be checked.
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Figure 3
Slow Breaker Example: Event Report

The first activated rule listed classifies the breaker operation as closing. The second rule points out the problem existing on the control dc voltage. An excessive voltage drop can be observed in the control dc voltage in. The next 6 rules are the basic rules, and they establish preliminary facts that most events features are delayed for this breaker. And this particular combination activates the complex rules indicating the breaker is slow and velocity is decreased.

IV. DATABASE DECISION-MAKING SUPPORT

While the data pre-processing and analysis help to improve the individual maintenance activities, the relational database is designed to support decision-making process. It builds up repository for history records, facilitates record retrieving based on versatile searches and provides statistical information for the stored data.

With the growing of database, history records for a particular circuit breaker can be used to develop a signal parameter- time curve. The curve in Figure 3 may indicate the deteriorate rate of the breaker operation. Before the condition developed into breakdown, maintenance can be applied to avoid the serious breakdown consequences. When the signal parameter reaches the dashed line, it can be interpret as a warning for immediate maintenance and inspection.
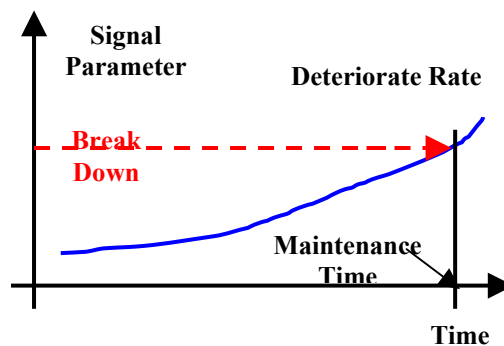
Figure 4
Circuit Breaker Deteriorate Rate

By gathering all the curves developed for one type of breaker, more accurate deteriorate rate can be developed. This deteriorate rate analysis can be used to predict the circuit breaker condition and schedule cost-saving maintenance.

Statistical information is able to trace the maintenance activities for each substation. For

instance, knowing how many circuit breakers in one substation has been tested and their conditions can provide guidance to future maintenance scheduling.

V. SYSTEM TESTING

Stable Performance

The records' collection and testing process can be divided into two phases. During the first testing phase, there is records selection bias in favor of abnormal cases, that is, the cases that have certain signal features and can fire certain expert system rules. No matter what features the signal might have, the analysis system is expected to produce results that confirm to what is observed in the signals. For example in Figure 5 three different features are under testing. The results in Figure 5 meet the expectation, and extracted signal parameter T5 conforms to the observed time point in Figure 5 when the Contact changes status.
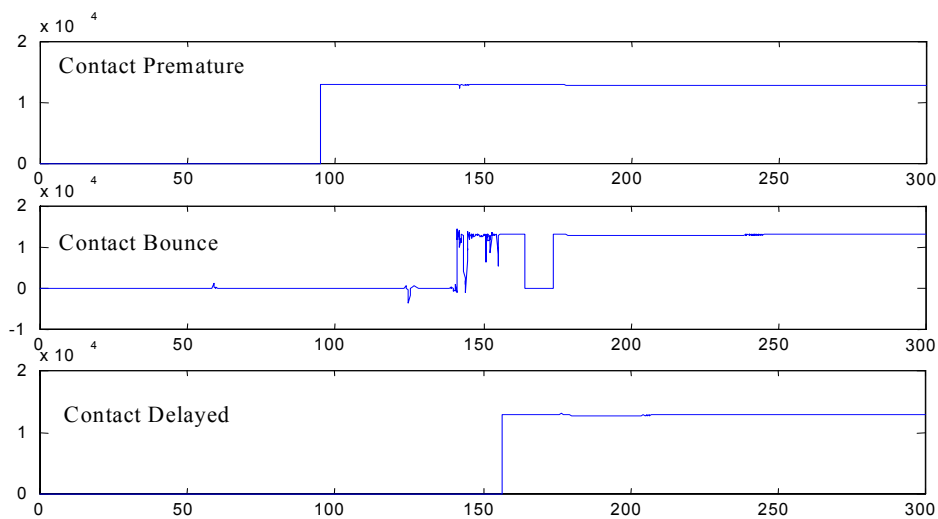

Figure 5
Function Testing For Contacts

Table 1

Test Results I

Case No.	T5 (ms)
1	95
2	141
3	156.5

Sometimes it is difficult to obtain actual data from in-service circuit breakers that match the desired signal features. In our case, one particular breaker is taken into a test shop to create certain operating conditions deliberately. Another method is to take a base record and manipulated the data in the software to create desired features.

Consistent Performance

During the second phase of testing, records are randomly collected. Features are unknown before the testing, and any undefined features may also appear in the test records. Some examples are excessive instrumentation noise, garbage waveforms or even missing signal channels due to an incorrect connection of test device. The analysis system is expected to differentiate these problems as unrelated to the breaker operation and provides stable results.

Usually, a set of good records from one breaker type is selected to build the breaker settings. Even though all the records are from the same manufacturer and belong to the same breaker type, difference in waveforms still can be clearly observed due to different operation condition of each circuit breaker. The analysis system is expected to produce consistent results despite the variance mentioned above. All the records that contain predefined features and fire the related expert system rules are diagnosed by the system. All the test cases that do not contain predefined features should not be diagnosed with these features by the system.

Figure 6 puts the coil currents of 18 records from same breaker type in parallel for comparing. The fourth case in the left column shows no obvious waveform at all, this might be attributed to a bad connection between the data acquisition unit and the circuit breaker control circuit. The eighth and ninth case in the left column have both been affected by strong noise. However, the noise takes different forms. For the eighth case, the noise is heavily added to the part when the coil current has already de-energized. For the case below it, the noise is evenly added to the whole signal channel.

The analysis system is expected to provide correct results for all the normal cases, that is, all the cases except the fourth case in the example (results for the dip time are provided in Figure 6). The result for the abnormal case could be meaningless, but that is not the problem with the pre-processing algorithm, nor will the pre-processing algorithm be responsible for detecting the abnormal case. Instead, expert system will be responsible for this task. Expert system is able to make a decision by combining all the information provided by different signal parameters. For the fourth case, the expert system will first find both signal parameters T2 (Event #2 Coil current picks up) and T4

(Event #4 Coil current drops off) equal to –1, which implies that coil current did not rise at all. Then expert system will summarize the condition analysis irrespective of the result of signal parameter T3 (Event #3 Coil current dip time).

The results of the pre-processing can be used to generate settings for the expert system. For the test cases provided in Figure 6, the average dip time is 79.58ms. The tolerance can be decided by getting the maximum deviation of the dip times from the setting 79.58, which is 3.76 ms in our example.
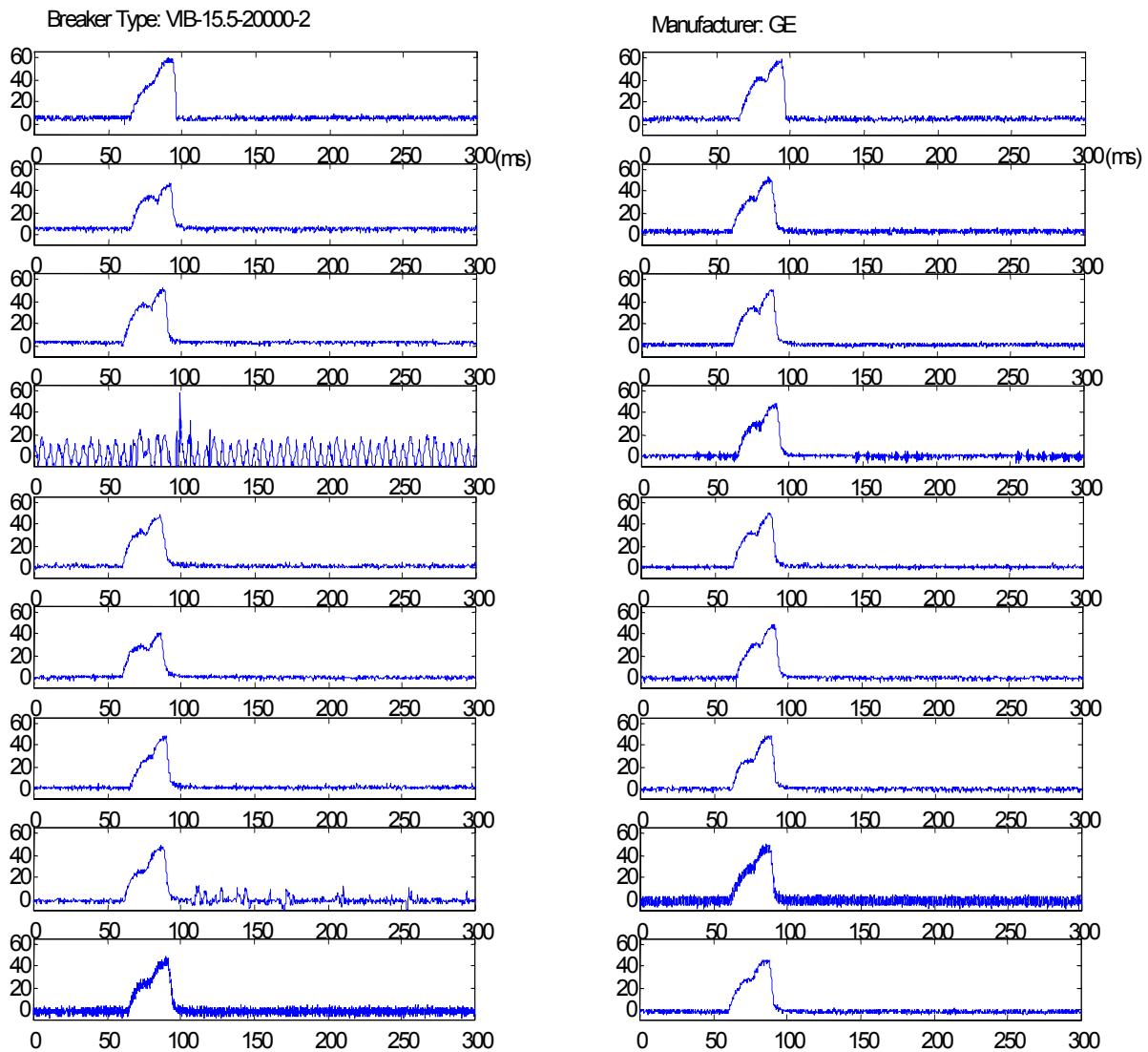

Figure 6
Coil Currents Of GE VIB-15.5-20000-2 Circuit Breaker

The overall testing in our case covered nearly 500 records from 31 different breaker types. The settings for the analysis system are customized for different breaker types.

Table 2

Test Results For GE VIB-15.5-20000-2 Circuit Breaker

Case No.	T2 (ms)	T3 (ms)	T4 (ms)
1	65.6042	80.5556	93.3819
2	65.2569	83.3333	94.0764
3	64.3889	83.3333	92.5139
4	64.5625	77.7778	96.6806
5	64.0417	80.5556	93.3819
6	64.5625	80.5556	94.2500
7	-1	69.4444	-1
8	63.8681	80.5556	93.3819
9	64.3889	77.7778	92.8611
10	64.2153	77.7778	93.2083
11	64.3889	77.7778	93.0347
12	64.3889	80.5556	92.5139
13	64.0417	80.5556	91.9931
14	64.5625	77.7778	89.9097
15	63.6944	77.7778	94.9445
16	64.0417	77.7778	93.2083
17	66.2986	80.5556	93.7292
18	64.9097	77.7778	93.9028

Limitations

The analysis system can only detect and classify problems that it was designed to analyze. If there are other abnormalities 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 abnormalities.

The decisions of the analysis system are also very sensitive to the settings that are used to detect the abnormalities. The settings must be configured by a person who has a good understanding of the rules and who understands how the settings affect the performance of the rules. Incorrect settings can cause the system to be oversensitive and detect everything as a feature or be under sensitive and not detect any feature. It should be noted once again that the settings are unique to each breaker type manufactured. If the wrong settings are used, then the system produces unpredictable

and unreliable results.

VI. CONCLUSION

To fully embrace the condition monitoring in the real world is not an easy task. The automated circuit breaker analysis system takes a step toward its realization by adding automated functions to the existing circuit breaker testing device. This system 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.

VII. REFERENCES

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Table 3

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 current 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

Table 4

Other feature definitions for cb performance indicators

Signal	Feature Description	Parameters
A & B Contact	Contact noise during the status change	NOI
	Contact bounce during the status change	BOU
	Contact has excessive drop during the high status	DIP
DC Voltage	DC Voltage has excessive ripples	RIP
	DC Voltage distortion	DIS
	DC Voltage has excessive spike(s)	SPI
	DC Voltage has excessive voltage drop	DIP
Trip & Close Initiate	Initiate signal drops off during the operation	DRP
Phase Currents	Phase current re-strikes	RES
X & Y Coil	X or Y Coil drops off during the operation	DRP
Trip & Close Coil Current	Coil current distorted when energized	NOI
	Coil current has excessive suppression when de-energizing	SUP