

REAL-TIME MONITORING AND ASSESSMENT OF CIRCUIT BREAKER OPERATIONS FOR DIAGNOSTICS AND CONTROL APPLICATIONS

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Abstract

Circuit breakers (CBs) are very important elements in the power system. They are used to switch other equipment in and out of service. Circuit breakers need to be reliable since their incorrect operation can cause major issues with power system protection and control. Today's practice in monitoring circuit breaker operation and status in real time is reduced to the use of Remote Terminal Units (RTUs) of Supervisory Control and Data Acquisition (SCADA) system to assess CB status. More detailed information about the control circuit performance may be obtained by CB test equipment typically used for maintenance diagnostics [1].

This paper addresses two important issues: a) how improved CB monitoring may be implemented in real-time, and b) what would be the benefits of such an implementation.

The results reported in this paper are coming from two research projects, conducted using funding from CenterPoint Energy and DOE-CERTS aimed at development of software for automated analysis of CB data and the other covering development of the CB data acquisition unit respectively.

The paper is devoted to description of a prototype implementation of a real-time CB monitoring system. The system consists of a new CB monitoring data acquisition IED that is located at circuit breaker and captures detailed information about its operation in real-time. The CB files are transferred to the concentrator PC where the application software performs automated analysis and makes an assessment about the operational status of the breaker. The software is based on signal processing and expert system processing. Application example using actual field data is discussed.

The paper ends with some conclusions, acknowledgments and a list of references.

Introduction

System wide real-time monitoring of circuit breaker operation and statuses currently is implemented using Remote Terminal Units (RTUs) of Supervisory Control and Data Acquisition (SCADA) system. Based on detected voltage levels on circuit breaker contacts, these units are providing information on final statuses of the circuit breakers such as "OPEN" or "CLOSE". The transitions in time of control signals, such as Trip or Close Initiate, X and Y coil currents, Control and Yard DC voltages, Closing Coil and others, used by protection and maintenance engineers for evaluation of CB performance cannot be monitored using RTU and SCADA approach.

A solution called Circuit Breaker Monitoring and Analysis (CBMA) developed at Texas A&M University, intends to solve described problems by integrating customized software and hardware solutions into a single, real-time monitoring and analysis system.

The system for real-time monitoring and analysis of circuit breaker operations described in this paper is an extension of widely used portable circuit breaker testing device concept [2]. The traditional testing devices are temporally 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 data are recorded. 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 is based on a new CB monitoring data acquisition IED called Circuit Breaker Monitor (CBM) which would be permanently connected to the substation CBs. CBM captures detailed information about each CB operation in real-time, regardless of whether the operation is initiated manually by the operator or automatically by the protection and control equipment and stores them in COMTRADE file format [3], [4]. As soon as the relevant CB control circuit signals are recorded and transmitted by wireless link to the concentrator PC, analysis software automatically performs the analysis.

CBMA provides better understanding of the condition and operating performance of each individual breaker by monitoring and analyzing expanded set of analog and digital signals from circuit breaker control circuitry. The advanced signal processing algorithms and knowledge base of the expert system implemented in the analysis software, significantly improve the reliability and consistency of the analysis results. Thanks to the fast and low cost CBM devices, new monitoring and control system described in this paper, enables permanent,

real time monitoring of status and performance of circuit breakers for the entire network.

In the first section of the paper, architecture of the whole system and basic processing algorithm are described. Second section explains the structure and basic functions of the hardware part of the system. Focus of the following section is on the organization of analysis software of the CBMA system. Basic building blocks, such as signal processing and expert system are elaborated and brief overview of knowledge base rules is given. At the end, an example of the stuck breaker case is illustrated with waveforms of relevant signals and expert system rules involved in problem detection process.

Architecture of CBMA system

The CBMA system supports client/server architecture. The client part resides in substation. It consists of the CBM devices attached to the CBs and a software running on concentrator PC, both permanently installed in the substation, as shown in Figure 1.

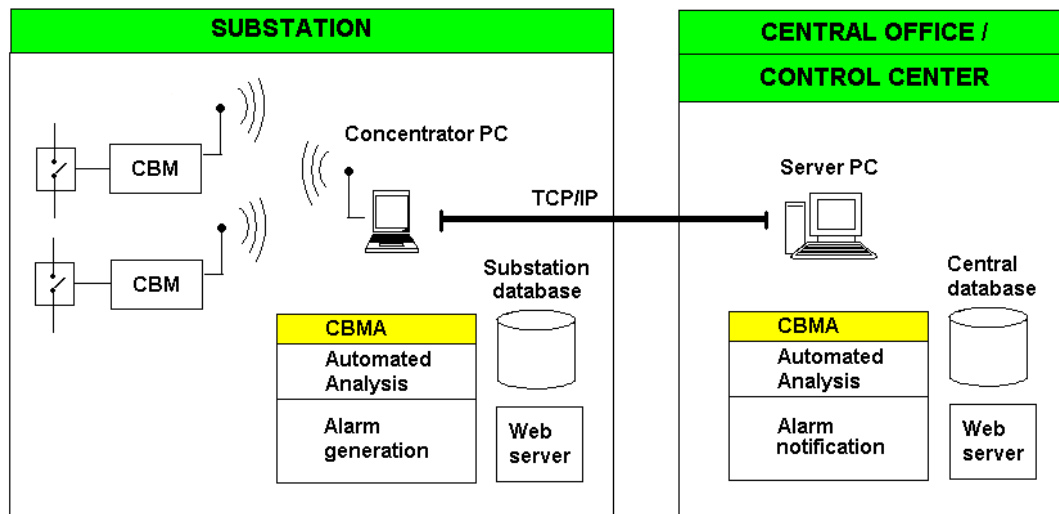


Figure 1
CBMA system architecture

When breaker operates, recorded files are wirelessly transmitted to the concentrator PC. The client application automatically performs the analysis of recorded signals from the circuit breaker control circuit. For more efficient data manipulation, IEEE file naming convention is used for naming the recordings files [5]. The signal processing module of the analysis software extracts various parameters from recorded signal samples and expert system evaluate them

against empirically obtained values and tolerances selected for specific type of circuit breaker.

The resulting report describes detected abnormalities and possible causes of the problem. If discovered problem presents serious threat to the reliability of future circuit breaker operation, programmable notification is sent to the server located in the central office. The notification is then processed and a warning is sent via email or pager to the maintenance and protection personal. Reporting is provided for both local and geographically dislocated users through implementation of local database and web server supporting information exchange through dynamic HTML pages.

Recorded files and reports can be downloaded to the server via Ethernet network relying on standard, fast and reliable TCP/IP protocol. In the central office or control center, the server part of CBMA consisting of the analysis module, a central database and master web server is running. The central database allows for easy archiving and retrieving of the records and analysis reports from all system substations. Master web application allows remote users to search for the records and/or analysis reports from anywhere on the corporate network (intranet).

Description of CBMA hardware

The system hardware in substation consists of circuit breaker monitors located on each breaker in the switch yard and a concentrator PC, used for gathering data, placed in the control room.

Circuit Breaker Monitor IED

The circuit breaker monitor IED (CBM) has three main tasks:

- Perform data acquisition of signals from the Circuit Breaker control circuit and record sequences of tripping and closing
- Convert captured signals into files according to COMTRADE file specifications
- Transmit files wirelessly to the concentrator device.

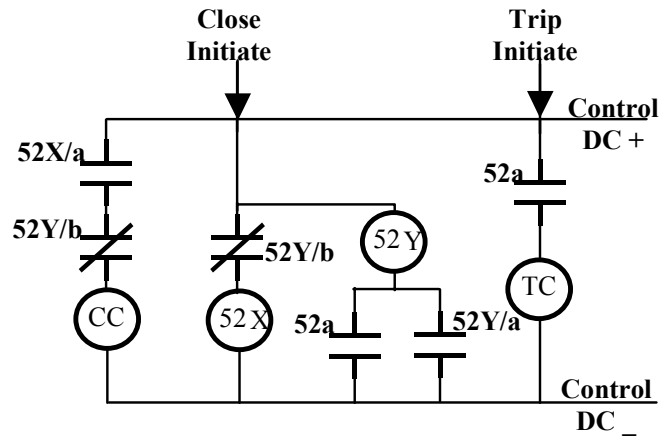


Figure 2
Control circuit of Circuit Breaker

The CBM IED monitors 15 electrical signals from the circuit breaker control circuit shown in Figure 1. The signals are generated during either tripping or closing of the breaker. Of these 15 signals, 11 are analog and 4 are status signals. The monitored signals are listed in Table 1.

Table 1
Signals of Circuit Breaker Control Circuit monitored by CBMA

Group	Signal name
Digital signals	Trip Initiate
	Close Initiate
	X Coil signal
	Y Coil signal
Contacts	"A" Contact
	"B" Contact
DC Voltages	Control DC Voltage
	Yard DC Voltage
	Light Wire
Coil Currents	Trip Coil (TC) Current 1
	Trip Coil (TC) Current 2
	Closing Coil (CC) Current
Phase Currents	Phase Current A
	Phase Current B
	Phase Current C

The most important signals are Trip Initiate and Close Initiate. These signals, initiated by the relay or the operator, cause generation of some other signals, as a result of the circuit breaker tripping or closing. All of the monitored signals are voltage signals. The signals representing currents are taken from shunts, thus converting them to appropriate voltage signals. In the worst case scenario time between the fault occurrence and the breaker lockout is about 1 (one) minute. The monitoring device is designed to record and store recorded data for this duration.

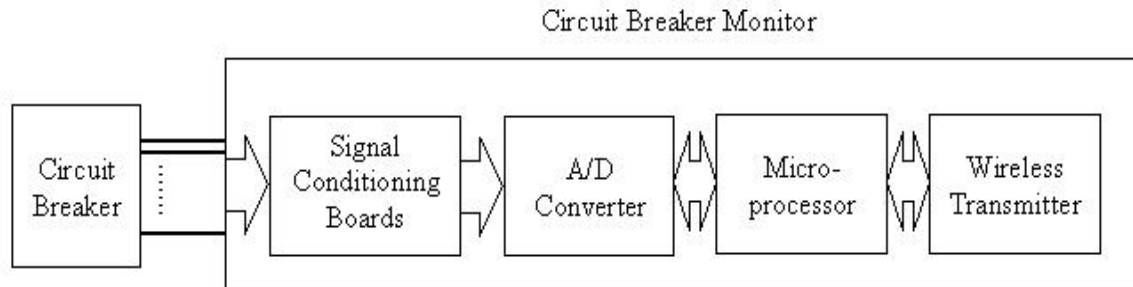


Figure 3
Block diagram of CBM

A block diagram of the Circuit Breaker Monitor IED is shown in Figure 3. The system consists of following modules:

1. **Signal conditioning boards:** The Signal conditioning and isolation module provides appropriate voltage levels for data acquisition. The voltage levels of signals at circuit breaker are either 130VDC or 1 VDC. The signal conditioning module conditions the input signals to be in the $[-5, +5]$ V range as required at the input of the A/D converter module. The module has adjustable gain for all 15 channels. A user determines suitable gain values for the hardware to be used with input signals during set up. The gain can be adjusted by software within a certain range for precise calibration in case of drift over time. The module also provides galvanic isolation of the signals at the input to prevent faults at the input of the module from damaging the rest of the system.
2. **Analog to digital converter:** The A/D converter employed has 16 channels and a 16 bit resolution. It takes the input from signal conditioning board and converts it to digital form. The sampling on the 15 channels utilized is synchronous. The sampling rate used is 5760 Hz but can be modified by software depending on the capability of the A/D converter.
3. **Microprocessor:** A microprocessor belonging to the x86 family is used for controlling the data acquisition and running the communication protocols. The microprocessor is equipped with 32 MB of memory to store 1 minute of data in case of offline monitoring.

4. **Wireless Transmitter** : A wireless system capable of transmitting data to distances over 200m is used for transmitting the recorded data to the concentrator PC. A transfer protocol for data transfer is established and the receiving software is set up appropriately. The transmission bandwidth of the transmitter for real time monitoring is chosen to be larger than 1.4Mbps ($5760\text{Hz} \times 15 \text{ channels} \times 16 \text{ bits}$).

Concentrator

The concentrator device consists of a high capacity wireless receiver connected to a PC which stores and processes data. The concentrator can be set in one of the two modes using the software.

1. **Continuous monitoring** : In this mode the concentrator continuously receives recorded data from each IED simultaneously. The transmission bandwidth required for this application is quite high , $n \times 1.4 \text{ Mbps}$, where n is the number of circuit breaker monitors in the system.
2. **Event monitoring**: In this mode the concentrator continuously polls the IEDs for their status and if any trip or close event has occurred the recorded data is uploaded. The transmission bandwidth for this application can be quite low as the data is transmitted offline.

Description of CBMA software

CBMA software consists of client and server part. Each of these contains several different modules, performing specific functions mentioned in previous sections of the paper. In this section, we will focus on functional requirements and implementation of the application for analysis of CBM recordings, whose architecture is displayed in Figure 4.

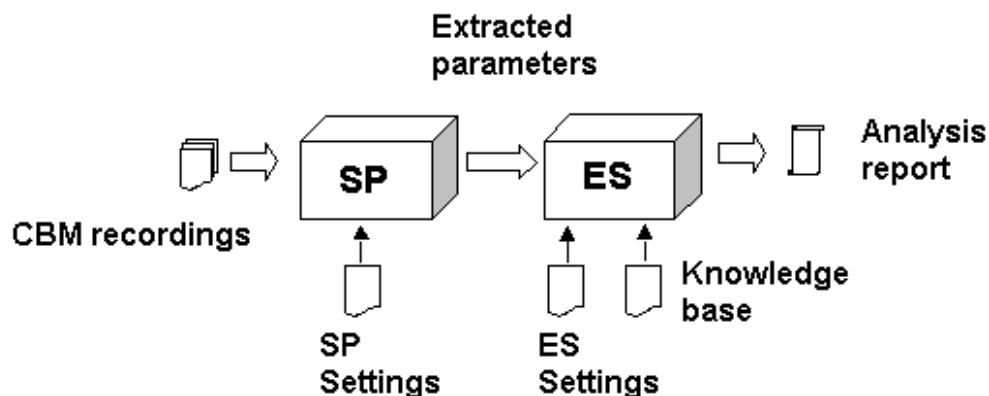


Figure 4
Architecture of analysis application of CBMA

Signal Processing

Signal processing module analyzes the data from CBM recordings using empirically obtained values of signal processing settings and extracts the signal features characterizing the transitions of the analyzed signal waveforms and describing them quantitatively. For example, some of the features extracted are time instances at which the coil current picks up or when the phase current breaks, a measure of voltage drop for the supply DC voltage, magnitude of the noise on the contact signal etc. Waveforms of CB signals are displayed in Figure 5.

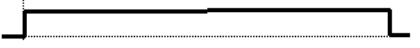
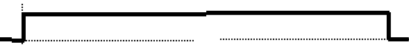




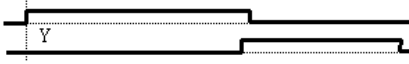
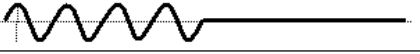
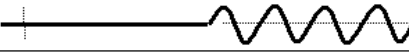
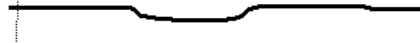
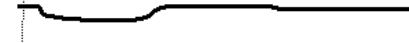
SIGNAL TYPE	WAVEFORMS	
	Circuit Breaker OPEN operation	Circuit Breaker CLOSE operation
Trip and Close Initiates		
"a" and "b" Contacts		
Trip and Close Coil Currents		
X and Y Coils	None	
Phase Currents		
DC Voltages		

Figure 5
Waveforms of signals from CB control circuit for open and close operations respectively

The signal processing consists of several steps, performed using advanced signal processing techniques. Fourier analysis is used for obtaining the information on frequency spectrum of the signal. For elimination of measurement noise, removal and extraction of unnecessary signal components of the frequency spectrum, digital filtering is being used. Wavelet composition and reconstruction algorithm is used for denoising and separation of signal features.

Expert system

Rule based expert system is implemented in CLIPS [6]. Purpose of the expert system in analysis application is to emulate reasoning of a human expert maintaining the circuit breakers. It compares the extracted signal features against the empirically obtained values. Each type of circuit breaker has particularly

customized set of rules used for the analysis of the expert system. A rule represents a fragment of knowledge that is used in the decision-making process.

Processing of the signal features by the expert system consists of several operations:

- Event classification – circuit breaker operation is classified such as closing or opening. Based on that conclusion, appropriate set of rules customized for each CB operation is used.
- Signal characterization and verification – each signal describing the event is analyzed based on the rules of the expert system knowledge base. The purpose of this is to verify that the values of extracted signal features conform to the expected values within given tolerances.
- Verification of cause-effect relationship among signals – the relationships involving multiple parameters and possibly multiple signals are analyzed to determine the causes of observed signal features.
- Operation verification – overall correctness of the breaker operation needs to be verified by comparing the actual breaker operation against the patterns stored in the rules of the expert system and the settings, each of them customized for particular type of circuit breaker and operation and specified by user.
- Analysis report generation – at the end of the analysis, expert system creates the report in the form of a text file. The report clearly describes the operation and performances of the circuit breaker, as well as maintenance and repair recommendations if problems are detected.

One of the advantages of rule-based expert systems is that they may be formed in hierarchal structure where some rules are simply intermediate steps to a final conclusion. When the expert system first begins to execute, all of the extracted features and settings (facts) are loaded into the short term memory. Once the facts are loaded, the inference engine uses the rules stored in long-term memory to analyze the information given in the facts. The rules were designed to enable the inference engine to perform two layers of analysis on the given data. List of expert system rules is given in Table 2 .

Table 2
List of expert system rules

R1	Breaker Opens	R38	CC Pickup Delayed
R2	Breaker Closes	R39	CC Pickup Premature
R3	TI Resets Prematurely	R40	CC Bad Suppression
R4	TI Drops Out	R41	Phase A: No Rise
R5	CI Resets Prematurely	R42	Phase A: No Drop
R6	CI Drops Out	R43	Phase A: Delayed
R7	Control DC Voltage Unstable	R44	Phase B: No Rise
R8	Control DC Voltage Rippled	R45	Phase B: No Drop
R9	Control DC Voltage Distorted	R46	Phase B: Delayed
R10	Control DC Voltage Spike	R47	Phase C: No Rise
R11	Yard DC Voltage Unstable	R48	Phase C: No Drop
R12	Yard DC Voltage Rippled	R49	Phase C: Delayed
R13	Yard DC Voltage Distorted	R50	Phase Time Violation [Pole Alignment]
R14	Yard DC Voltage Spike	R51	Breaker Re-strike
R15	"a" Contact Unstable	R52	X Coil No Activation
R16	"a" Contact Noisy	R53	X Coil Activation Delayed
R17	"a" Contact Bounce	R54	X Coil No Deactivation
R18	"a" Contact Premature	R55	X Coil Deactivation Delayed
R19	"a" Contact Delayed	R56	X Coil Deactivation Premature
R20	"a" Contact Flat	R57	X Coil Drops Out
R21	"b" Contact Unstable	R58	Y Coil No Activation
R22	"b" Contact Noisy	R59	Y Coil Activation Delayed
R23	"b" Contact Bounce	R60	Y Coil Activation Premature
R24	"b" Contact Premature	R61	Y Coil No Deactivation
R25	"b" Contact Delayed	R62	Y Coil Deactivation Delayed
R26	"b" Contact Flat	R63	Y Coil Drops Out
R27	TC Current Flat	R64	Breaker Opening Slow
R28	TC Current No Drop	R65	Breaker Closing Slow
R29	TC Current Distorted	R66	Stuck Breaker (Opening)
R30	TC Current Dip Delayed	R67	Stuck Breaker (Closing)
R31	TC Pickup Delayed	R68	Velocity Decreased
R32	TC Pickup Premature	R69	Velocity Increased
R33	TC Bad Suppression	R87	Phase Currents No Rise/No Drop – Repair Statement
R34	CC Current Flat	R88	X/Y Coil Activation Premature/Delayed – Repair Statement
R35	CC Current No Drop	R89	X Coil No Deactivation – Repair Statement
R36	CC Current Distorted	R90	X Coil Deactivation Delayed – Repair Statement
R37	CC Current Dip Delayed	R91	X/Y Coil Premature/Delayed – Repair Statement
R70	Effect of Binding on "a" Contact	R92	Y Coil No Deactivation – Repair Statement
R71	Effect of Binding on "b" Contact	R93	Velocity Decreased – Repair Statement
R72	Sequence A-B Violated	R94	Velocity Increased – Repair Statement
R73	Friction in Trip Assembly	R95	Travel Time Decreased – Repair Statement
R74	Close Coil Armature-Latch Friction	R96	Travel Time Increased – Repair Statement
R75	Travel Time Decreased	R97	Effect of Binding – Repair Statement
R76	Travel Time Increased	R98	Breaker Re-strike – Repair Statement
R77	Trip Latch Maladjustment	R99	Default Repair Statement
R78	Close Assembly Maladjustment		
R79	TI/CI Output Statement		
R80	Control/Yard Output Statement		
R81	"a"/"b" Contact Output Statement		
R82	TC/CC Flat – Repair Statement		
R83	TC/CC No Drop – Repair Statement		
R84	TC/CC Distorted – Repair Statement		
R85	TC/CC Dip Delayed – Repair Statement		
R86	TC/CC Pickup Premature – Repair Statement		

Figure 6 shows a graphical representation of the two layers of analysis.

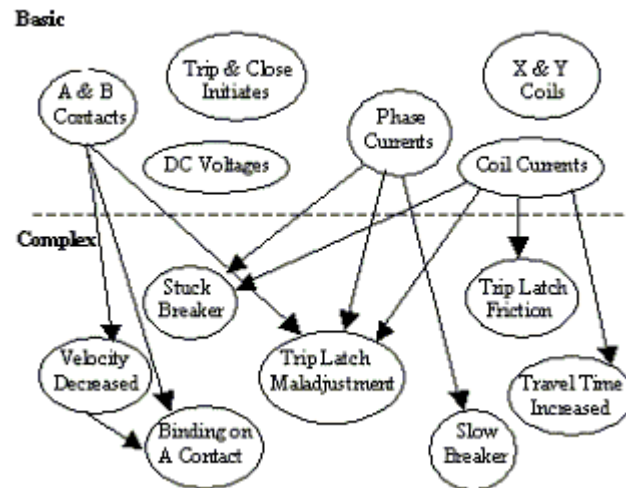


Figure 6
Layers of expert system analysis

The first layer uses a set of basic rules 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 circuit breaker condition. The second layer uses a set of complex rules to analyze the interrelationship between all of the activated rules from the first stage. Based on which rules were activated, 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 expert system was designed to only analyze a single event or operation at a time. In the case of multiple operations, the data is divided up into a group of single operations and fed into the expert system separately. The results from each layer of the analysis are logged to an analysis report. The report provides useful information about the circuit breaker operation to enable maintenance personnel to fix the problems that are discovered.

Example of Analysis

A typical example is given to demonstrate the analysis results obtained by the CBMA solution. The example chosen for this discussion is a breaker that becomes stuck while opening. This is a common problem found in breakers out in the field and is certainly a problem that requires immediate maintenance. The problem can be diagnosed by analyzing four signals that include the three phase currents that are monitored using the current transformers and the trip coil current that is monitored from the control circuit. The signal abnormalities that characterize this type of problem are displayed in Figure 7.

The trip coil current remains at its maximum steady state value and one or more phase currents do not drop to zero. Only one phase current is shown because one abnormal phase is sufficient to detect and classify the problem. The other phase currents may be normal or abnormal.

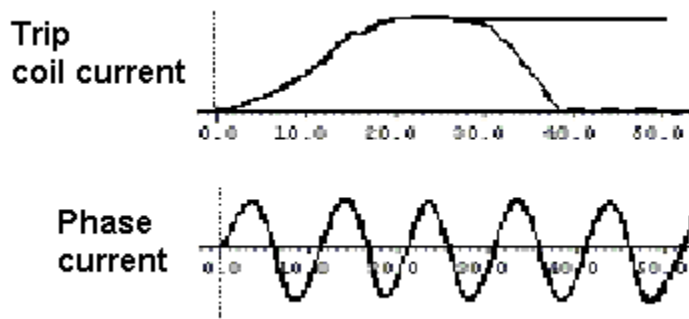


Figure 7
Signal abnormalities for a stuck breaker

In the signal processing stage, the program extracts two time parameters that correspond to the time instants where the trip coil goes to zero and the time instant where the phase current goes to zero. If a signal does not make a transition to zero, then the corresponding time parameter is replaced by a minus one. These parameters are sent to the expert system for analysis. The expert system uses two basic rules to determine if the trip coil and phase currents go to zero. When both basic rules become activated, a complex rule called *stuck breaker* also becomes activated to indicate the breaker had a problem during the opening operation. The complex rule for a stuck breaker is given in Figure 8. Rules 69, 72, and 75 (indicated in Table 2) check that each of the phase currents made a transition to zero. Rule 24 analyzes the trip current fact to see if it made transition to zero.

```

(defrule R61
  (declare (salience -1280))
  (initial-fact)
  (closing)
  (not (R61_fired))
  (or (R69_fired) (R72_fired) (R75_fired))
  (R24_2_fired)
=>
  (assert (R61_fired))
  (printout t crlf " R61: Stuck breaker while closing!" crlf)
  (printout outFile " R61: Stuck breaker while closing!" crlf)
)

```

Figure 8
Complex rule for stuck breaker

Conclusions

The new CBMA system for real-time monitoring and assessment of circuit breaker operations provides for better understanding of condition and operating performance of each individual breaker by monitoring and analyzing expanded set of analog and digital signals from circuit breaker control circuitry.

Permanently monitoring and automatically analyzing the circuit breaker data recorded for each operation enable real time monitoring of integrity and topology of the entire power network.

This solution facilitates the analysis process by providing timely results that are consistent, irrespective of who runs the analysis. Enhanced reasoning, consistency and speed are achieved by using advanced signal processing and expert system techniques.

The archiving and retrieving functions supported by database and web server, enable an easy access to the historical data, reports and dissemination across the company.

System features high speed, network wide, programmable trouble notifications.

Using low cost, off-shell components for implementation of Circuit Breaker Monitor (CBM), cost of the system is significantly lowered.

Wireless link for communication and transfer of data from CBM to the concentrator PC increases the flexibility of the system which provides important advantage over hardwired solutions.

Acknowledgments

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