Automated Circuit Breaker Monitoring and Analysis

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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. The testing devices can be connected to the circuit breaker's control circuit to record analog and digital signals. The automated system consists of a signal processing module and an expert system module. The two modules process the voltage and current signals recorded by the testing device, 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 process. Real data recorded in a substation has been used to test the system.**

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

I. Introduction

THE circuit breakers represent one of the most critical power apparatus in the power system. They are used to switch the topology of the power system to accommodate various configurations for routing the load. At the same time, the breakers are used to isolate faulted parts of the system. Due to such a critical role, the breakers need to be ready to operate at all times and any disruption in this operation may have costly consequences. To prevent circuit breaker miss operation, the breakers are inspected and maintained on a regular basis. In performing such task, one obstacle is quite obvious: an average size utility may have thousands of breakers in service. The large number of breakers makes it difficult and economically infeasible to perform the inspection and maintenance frequently enough to achieve the desired circuit breaker reliability. As a matter of fact, the maintenance cycle may be up to ten years, which leaves room for a number of early signs of deteriorating performance to go undetected.

Typical circuit breaker inspection practice is to use portable test sets that are carried to a substation and connected to the breaker manually by the maintenance staff [1]. Prior to testing, an alternate source is paralleled with the circuit breaker under test to prevent an interruption of the circuit breaker load. Once the test set is connected, the circuit breaker is manually forced into operation and the recordings of signals from the control circuitry are taken. The maintenance crew analyzes the recordings on the spot and, if abnormalities are detected, the appropriate breaker maintenance or repair procedure is initiated. This process is rather tedious and subject to interpretation and particular expertise of the individuals involved. As a result, the inspection conclusions and subsequent actions may vary from crew to crew. Interpretations of the circuit breaker recordings may result in different levels of readiness of the circuit breakers even after the inspection or specific maintenance is performed.

The two mentioned problems, namely the large number of breakers causing the long intervals between inspections and the diagnosis inconsistency causing incomplete or ineffective maintenance, led the utilities to consider more efficient and consistent means of monitoring and analyzing breaker operations. This paper presents a solution that is based on the use of advanced signal processing and expert system concepts. The implementation is aimed at developing a set of software modules for automated analysis of circuit breaker conditions. The system collects samples of signals obtained from a circuit breaker control circuitry, extracts the required signal features and passes the features to an expert system for determining the final conclusions. Since the whole process is automated, the time required to perform the diagnosis and maintenance may be significantly reduced. At the same time, since the rules for the analysis are hard coded, the diagnosis is very consistent. Future application is envisioned where this system uses a permanently installed data acquisition unit on each breaker. In that case, each breaker operation throughout the system would be analyzed on line and just-in-time maintenance strategy can be implemented. The main features of the demo system developed for a major utility are described.

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The first part of the paper describes requirements for analysis of circuit breaker operations. This is followed by a discussion of the subsystems for parameter extraction and expert system analysis. An example of how the system may detect and analyze a case of a stuck breaker is given next. Conclusions and references are given at the end.

II. REQUIREMENTS FOR ANALYSIS OF CIRCUIT BREAKER OPERATIONS

A. Circuit Breaker Operation

The switching operation of a circuit breaker is best described through an explanation of its control circuit. Fig. 1 displays a simplified version of a commonly used control circuit called the X-Y relay scheme. The schematic can be divided into two sections where one section controls the opening sequence and the other section controls the closing sequence.

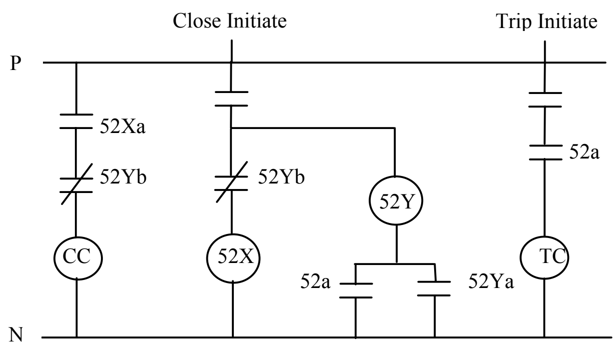


Fig. 1. Simplified Control Circuit Schematic

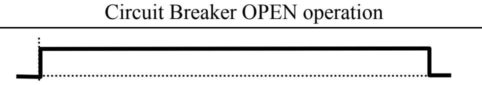
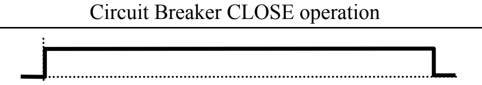
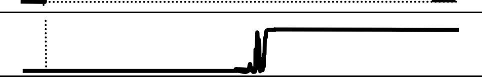
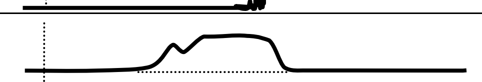
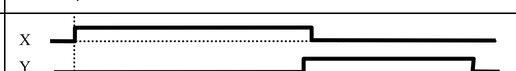
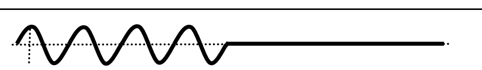
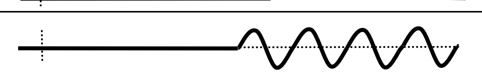
The section that controls the opening sequence includes the branch that contains the trip coil (TC) and circuit breaker (52a) auxiliary contact and the section that controls the closing sequence includes all the remaining branches in the circuit diagram. Table I shows how various signals monitored in the control circuit change throughout opening and closing operations.

When a circuit breaker is in the closed state, operation begins with a trip initiate signal being sent to the control circuit from an operator in the control house, a relay, or some other control device. Since the circuit breaker is initially in the closed position, all the 52a contacts are also in the closed position. The closed contacts allow the signal to travel down the trip wire to the trip coil labeled TC in the figure. The trip initiate signal energizes the trip coil that in turn creates a trip coil current as shown in Table I. The coil current is measured across a shunt that is placed in series with the trip coil.

The trip coil typically contains a plunger mechanism that is pushed out of the coil when it becomes energized. When the plunger is pushed out of the coil, it exerts a force on a latch that releases the stored energy in the breaker. A compressed spring is normally used as the energy source to trip the circuit breaker. The stored energy is used to move all of the mechanical parts within the breaker and open the main interrupting contacts. As the breaker opens its main contacts, the circuit breaker auxiliary (52a) and (52b) contacts change state and the phase currents go to zero. When the breaker reaches the open state, all (52b) contacts are closed, all (52a) contacts are open, and the breaker is ready to be closed when needed.

A close operation is initiated by sending a close initiate signal down the close wire of the control circuit. The close initiate signal reaches the X Coil (52X) immediately after the initiate signal is sent because the (52Yb) contact is in the closed position. The X Coil becomes energized and closes the (52Xa) contact in the control circuit. The closing of the (52Xa) contact allows control DC to energize the close coil labeled CC in the figure. The close coil operates like the trip coil by pushing a plunger out of the coil. It is shown in Table I that the trip coil and close coil have similar waveforms. The plunger exerts a force on a device that releases stored energy allowing the breaker to close its main contacts. As the main contacts close, the movement of the mechanical parts also closes all the auxiliary (52a) contacts and opens all (52b)

TABLE I
SIGNAL WAVEFORMS

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		

contacts. This creates an electrical path from control DC to the 52Y coil. The 52Y coil energizes and changes the state of all the 52Y contacts in the circuit. The 52Y coil remains energized until the close initiate signal has been removed. Once the main contacts have closed, current in all three phases begin as shown in Table I. Note that there is an open 52Y contact in the close coil branch that prevents the close coil from becoming energized again until the first close initiate signal has been removed. This is called an anti-pumping arrangement that only permits a single close operation for a single close initiate signal. If the breaker should open while the close initiate is still active, the breaker will not close again until the close initiate signal has been removed and reapplied.

B. Abnormalities

Under existing maintenance procedures, signal records for each circuit breaker are acquired over time and archived. An experienced maintenance crew usually keeps one reference record for each type of circuit breaker to compare against all future records. When significant signal abnormalities are observed, maintenance is performed on the breaker to correct the problem.

Following the cause and effect order, the signal abnormalities definition will be described first. Then, possible breaker problems associated with some abnormalities will be provided as examples. This categorization process must be expanded in great detail before a complete expert system knowledge base can be developed.

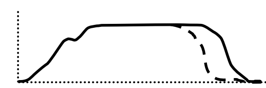
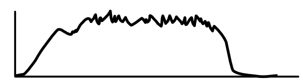
TABLE II
WAVEFORM ABNORMALITIES

SIGNAL TYPE	OBSERVED ABNORMALITIES
Trip or Close Initiate	Signal resets prematurely
A or B Contacts	Abnormal noise on contacts Contacts bounce Response time is increased Response time is reduced Dropout during trip operation
Trip or Close Coil Currents	Dip delayed Delayed drop-off or no drop-off Distorted waveform Current flat Current pick-up delayed Current pick-up premature
X & Y Coils	Late or no activation Late or no deactivation Premature deactivation
Phase Currents	No drop or no rise
DC Voltages	Voltage drops below threshold Oscillations on the waveform Noise (distortion) Spike

The signals have been divided into six groups and a simplified summary of signal abnormalities for each group is provided in Table II. Some abnormalities like *delayed* and *premature* are related with the time axis. For example, a contact is delayed means that the contact makes its transition (i.e., from low to high or vice versa) later than it should. Some abnormalities like *ripple*, *spike*, and *noise* are related with waveform, and some abnormalities are related with the signal amplitude.

The breaker problems can be associated with the signal abnormalities. The trip and close coil currents are given here as an example. In Table III two abnormal coil currents are shown in figures and described briefly in text. The dashed line represents the normal signal while the solid line represents the abnormal one in the figures. The last column of the table provides the possible breaker problem associated with the abnormalities.

TABLE III
SUMMARY OF ABNORMAL COIL CURRENT WAVEFORMS

Abnormal Type	Illustration	Potential Breaker Problem
Coil Current Drop-off Delayed		Friction or Binding
Coil Current Distorted		Defective Coil

III. SYSTEM FOR AUTOMATED ANALYSIS OF CIRCUIT BREAKER OPERATIONS

A. Parameter Extraction

The role of the signal-processing module is to extract the pertinent signal parameters from the samples of signals obtained from the circuit breaker control circuitry. The extracted parameters are passed to the expert system module. The expert system classifies a circuit breaker operation using a set of rules that operate on these parameters.

The signal parameters were chosen to represent the most relevant signal features used in making a decision about the circuit breaker operation. Identifying the parameters that carry required information about the signal features is crucial for the entire analysis.

Take the Trip Coil current as an example. A normal Trip Coil (TC) current makes a gradual transition to a nonzero value immediately after the Trip Initiate is activated. TC current continues to increase at a steady rate until it reaches a small dip towards the top of the waveform as shown in Fig. 2. The dip corresponds to "the point where the trip coil has released the trip linkage to allow the breaker mechanism to operate" [2]. The dip at TIM2 in Fig. 2 is caused by the change in the reluctance of the trip coil. Then, the TC current may rise slightly or remain flat at its maximum value until it starts dropping down. This period is referred to as the mechanism travel time. The TC current signal should be fairly smooth except for the dip at the beginning of the waveform.

For a Trip Coil current signal, five parameters illustrated in Fig. 2 are selected to represent its features. The Trip Coil current signals exhibit several different types of abnormalities.

One type of abnormality found in the coil current is a delayed transition to a nonzero value. If the pick up of Trip Coil current is delayed, it will be represented by the parameter TIM1. Other parameters are defined in a similar way to characterize certain features in the signal.

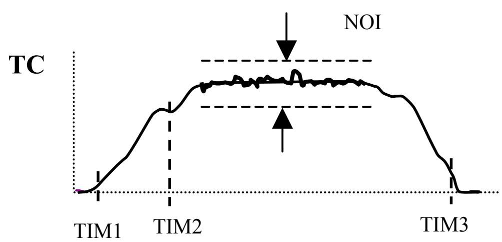


Fig. 2. Trip Current waveform and parameters

The algorithms for parameter extraction follow a four-step procedure as shown in Fig. 3. In the first step, preparation, all the recorded signals are checked and any noise is removed. For different breaker types and different operations (TRIP or CLOSE), the signals may not all be present due to the diversity of secondary circuitry.

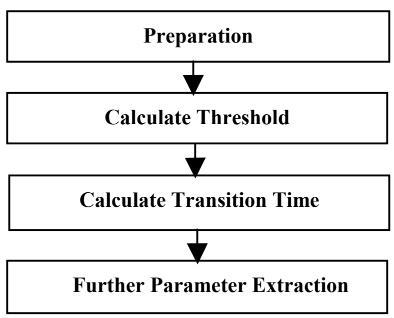


Fig. 3. Parameter extraction process

A one-by-one check makes sure which signal is available and valid. A wavelet denoising technique is used to facilitate extraction of signal features that may be disguised by the instrumentation noise. This is accomplished by first performing a discrete wavelet decomposition. For good results, the signal is decomposed to level 3 with the Daubechies #6 (Db6) wavelet [3]. After the signal has been decomposed, it is denoised with a soft thresholding technique and then reconstructed.

The threshold calculated in the second step is related to the signal amplitude. The Trip Initiate or Close Initiate signal represents a trip or close command sent to the circuit breaker either manually or by a relay, and they are usually processed first. Their thresholds are signal amplitude average multiplied with a changeable factor. After processing the initiate signals, the trigger point of a trip or close event is obtained. The thresholds for other signals are the average of pre-trigger amplitudes multiplied by a changeable factor.

One of the most important features of the signal is when it changes its state (high to low or low to high). The third step determines the time when the transition occurs. For some signals, there are no more features to be extracted but for other signals, more processing is required in the fourth step.

B. Expert System Analysis

The analysis of circuit breaker recordings is performed by a rule-based expert system implemented in CLIPS [4]. The purpose of developing an expert system was to emulate the decision-making process of a human expert [5]. The system was designed and developed through extensive interviews with a group of experts at Reliant Energy HL&P who have experience in analyzing circuit breaker records. The interviews enabled the designers to extract the human expertise and place it into an expert system that could emulate the reasoning of the experts. By preserving knowledge in an expert system, it ensures that the analysis of all future recordings will be performed in a consistent manner.

An expert system consists of three main components that include short-term memory (STM), long-term memory (LTM), and an inference engine as shown in Fig. 4 [5]. The short-term memory and the long-term memory collectively make up the knowledge base.

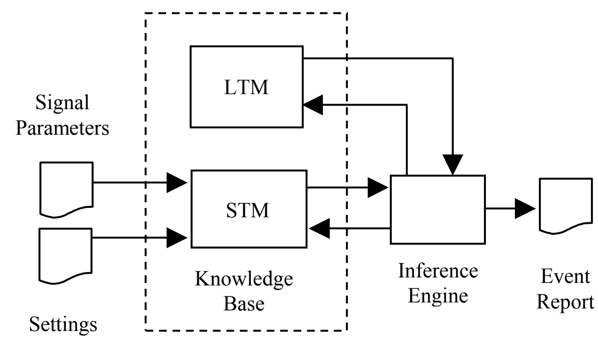


Fig. 4. Expert system analysis process

The short-term memory consists of pieces of information called facts [4]. In this particular expert system, two types of facts were implemented: the parameters extracted from the signal processing module and the settings for each of the parameters. Many of the settings contain a set value and a tolerance. The set value represents the expected normal value for a parameter and the tolerance specifies the degree of freedom that the parameter is allowed to deviate and still be considered normal. There are also other settings that specify a maximum limit that the parameter must be under to be considered normal. There is at least one fact for each signal processed by the signal processing module and there is at least one fact representing a setting for each signal. Each fact contains the name of the signal and all the parameters associated with that signal. Likewise, each setting fact contains all the settings that pertain to a particular signal. The facts for the settings and signal parameters are each stored in separate ASCII text files that are loaded into the system at run time.

The long-term memory is the location where all of the expert system rules are stored. A rule represents a fragment of knowledge that is used in the decision-making process [4]. It is formulated as an "if-then" rule where the "if" portion of the rule is called the antecedent and the "then" portion is called the consequent [4]. The antecedent specifies a set of criteria that must be satisfied for the rule to be activated. When a rule becomes activated, then the actions specified in the consequent are performed. The consequent may give a final decision about status of the breaker or it may simply be an intermediate conclusion that is used by other rules to make more complicated decisions. 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 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. Fig. 5 shows a graphical representation of the two layers of analysis.

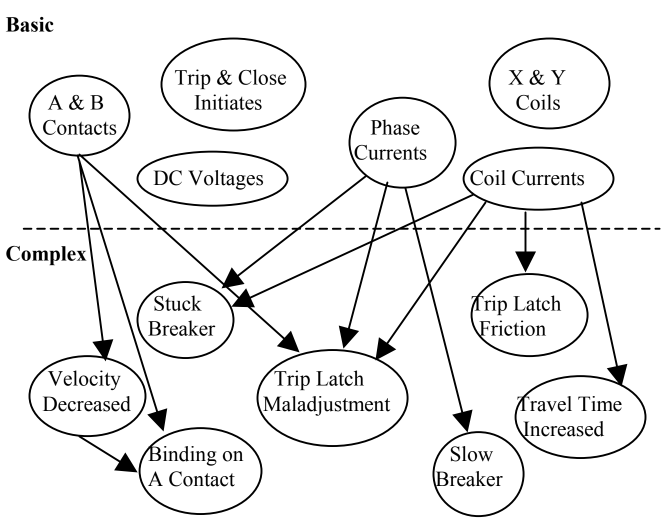


Fig. 5. Layers of Analysis

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 expert system event report. The event report provides useful information about the circuit breaker operation to enable maintenance personnel to fix the problems that are discovered.

IV. Example

A typical example is given to demonstrate the signal processing and expert system analysis. 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 Fig. 6. 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.

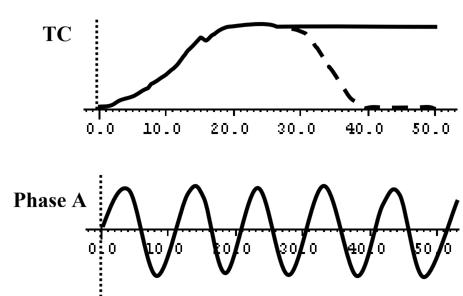


Fig. 6. Signal abnormalities for a stuck breaker

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 placed into a facts file and sent to the expert system for analysis. The expert system uses two basic rules to establish that 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 Fig. 7. Rules 69, 72, and 75 check that each of the phase currents made a transition to zero. Rule 24 analyzes the trip current fact to see if it made a 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)
)
```

Fig. 7. Complex rule for stuck breaker

V. CONCLUSIONS

The paper illustrates the following main features of the solution:

- Circuit breaker operation can be monitored and analyzed in an automated way using advanced signal processing and expert system techniques.
- Signal processing has to be capable of extracting relevant features of the signals recorded from the circuit breaker control circuitry during breaker operation.
- Expert system has to have sufficient facts and rules to be able to detect abnormalities in the breaker operation based on the extracted signal futures.
- By performing the automated analysis, two main goals are achieved: reduction in the time needed to detect an abnormality and, consistency in performing the analysis.

VI. ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of Dr. Zijad Galijasevic, a former TAMU graduate student, for his work on the development of the expert system.

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VIII. BIOGRAPHIES

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