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Trip Coil Signature Measurement and Analysis Techniques for Circuit Breaker

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***Abstract* — The Condition Based Maintenance (CBM) is a maintenance strategy that uses the actual condition of the asset to decide what maintenance needs to be done. The trip coil signature analysis for circuit breaker offers a cost-effective methodology in fulfilling the CBM requirement. In this paper, analysis of trip coil signature in circuit breakers is discussed together with different perspectives in implementing their methodologies. This analysis provides the essential insights from the perspective of mechanical degradation and control circuit reliability in assessing the performance of circuit breaker operation in switchgear. Finally, this paper disseminates the knowledge of the trip coil signature analysis methods, which leads to more effective switchgear maintenance practice in CBM.**

Keywords - Circuit breaker (CB); Switchgears; Condition Based Maintenance (CBM); Fault Diagnosis

I. INTRODUCTION

Circuit breaker is the main component inside switchgear design. It is mechanically designed to break and to connect the electrical connection between the source and the load. The mechanical design of circuit breaker is very complex in order to control the interrupting medium to extinguish the arc [1]. However, the mechanical operation of circuit breaker also relies on the electrical signal and sensor in order to ensure smooth operation. The unique relationship between the mechanical design and the electrical design in circuit breaker, particularly the trip coil, provides a significant tool for engineers in performing failure investigation.

It is subsequently realized that the trip coil signature analysis can be easily exploited as a powerful and economical tool in assessing the condition of circuit breaker. However, such analysis is rather complicated and can only be performed by experienced engineers with a distinctive knowledge of circuit breaker operation and switchgear design. As the result, the trip coil signature analysis is very subjective to an individual, and it is very difficult to pass on the knowledge from one engineer to another. The important key in analyzing the trip coil signature is the analytical interpretation [2]. This is due to the multidimensional features that appear on it. On another perspective, circuit breaker is often associated with the sluggishness, which is associated with the problem of slow operation, failure to trip or failure to close of circuit breakers. Based on the statistic, most of the failures in field are related to operating mechanism and control circuits [3] [4] [5] [6] [7].

Currently, the trip coil signature analysis is important for maintenance engineer to obtain the initial assessment of circuit breaker operation in switchgear. With a strategic and proper analysis, the trip coil signature analysis serves as key tactical tool in providing a reflection of performance according to Condition-based Maintenance (CBM) practice. Eventually, it potentially optimizes the preventive and corrective maintenance activities for switchgear as well as minimizes the Operation Expenditure (OPEX) for having such maintenance activities. Hence, it is crucial to review and to understand the fundamental concept in the trip coil signature analysis so that further improvement can be made to simplify the analysis process.

II. TRIP COIL SIGNATURE – THEORY AND CONCEPT

The trip coil signature contains features that can be regarded as a unique signature, which is similar to the fingerprint of human. The data features, such as latch time, buffer time, main contact time, auxiliary contact time, end time and the current ratio can be captured from the trip coil profile. These features eventually reflects the signature of circuit breaker, which may be associated to the finer aspects of the performance of the circuit breaker, in which each parameter may indicate the condition of different parts in the switchgear.

The electromechanical property of the switchgear allows for the trip coil to act as a circuit breaker profiler, where the current fluctuations can be represented graphically for analysis. The trip coil is operated to activate the plunger, and hence it is used as a current sensor, in where a time-based current reading is logged to depict the behavior of the trip exercise. Fig. 1 shows a standard trip operation sequence.

Commencing with Fig. 1(a), when the trip coil is energized by an external direct current (DC) supply, the current builds up to the first summit Ipk1, as indicated in Fig. 2. This indicates that the plunger, which is targeted towards hitting the latch of the spring mechanism, overcomes the mechanical resistance and the effect of “stiction” in order to be in motion.

As the plunger moves toward the latch [Fig. 1(b)], the rate of current increase is dampened and subsequently increases again to I_{pk2} as the plunger hits the latch, which

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demonstrates the principle of energy conservation. The current magnitude descends again as the plunger overcomes the latch until it strikes the buffer (depicted as buffer time, Fig. 2). The current increases to I_{pk3} (in Fig. 2) while the plunger ceases the motion abruptly.

Consequently, all three phases' current values are logged, shown in Fig. 2 as Main Contact Time 1, 2 and 3. The contacts trips, as shown in Fig. 1(d) ensued by the brief interval before the auxiliary contacts opens as well, as shown in Fig. 1(e) and Fig. 2, at the Auxiliary Time. At this point, the energized coil's current supply is severed, and the remaining inductive energy in the trip coil dissipates depending on the inductance, as shown in Fig. 2, at End Time. After demagnetizing of the coil, the plunger returns to the default position as shown in Fig. 1(f).

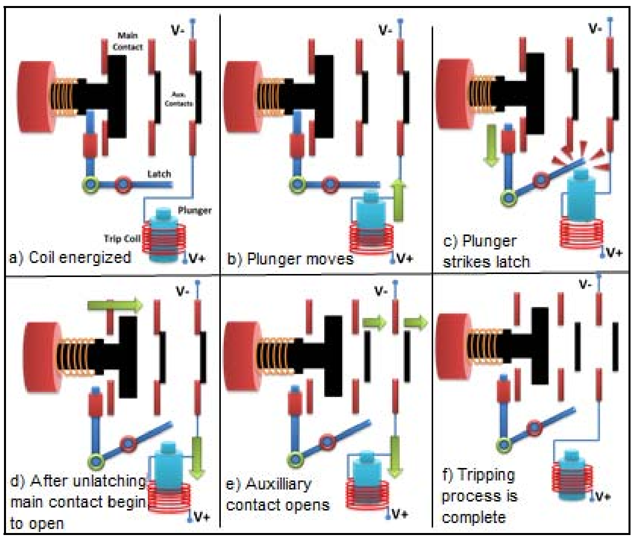

Figure 1. Trip coil mechanism (Redrawn from [8])

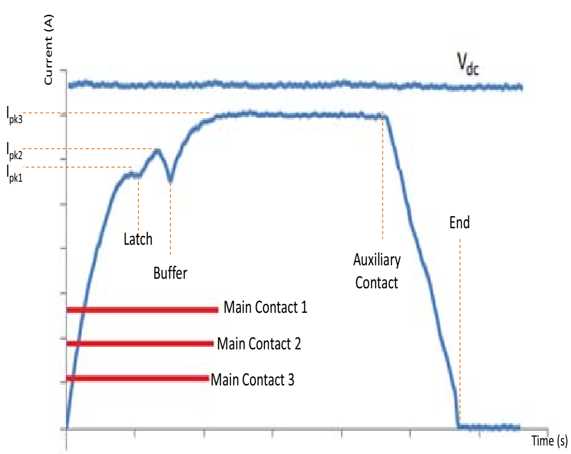

Figure 2. Trip coil signature and the features

III. Measurement and Analysis

There are two important aspects in investigating the trip coil signature, namely measurement and analysis technique.

A. *Measurement Technique*

The idea of using trip coil signature originally comes from the earliest and the most successful method called "Timing Test" [9] [10]. The Timing Test focuses on two main operation of circuit breaker, namely Close (C) and Open (O). Eventually, there are four variants of circuit breaker operations - Close (C), Open (O), Reclose (O-C) and Trip-free (C-O). However, most utilities are interested in investigating the mechanical behavior of circuit breaker operation under O-C-O throughout the entire sequence. In general, the measurement of trip coil signature is taken by measuring the current that going through the physical trip coil circuit. In addition, the trip coil signal is compared against the signals of respective Main Contact as shown in Fig. 3. The signal of DC voltage supply is also included in order to consider power supply stability, which normally reflects the DC supply used in the substation. This measurement technique is normally applied in Timing Test of circuit breaker.

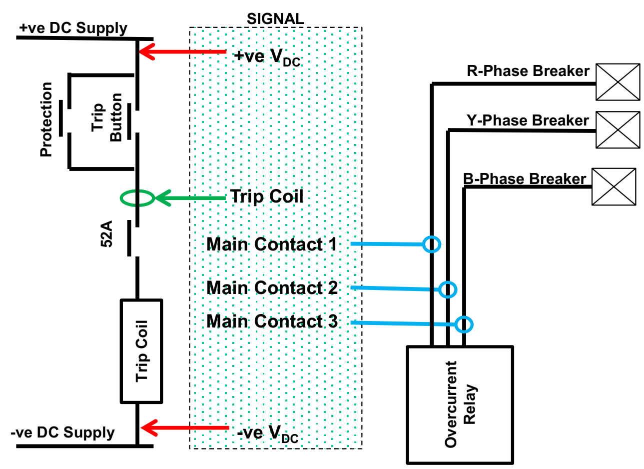

Figure 3. Measurement Technique for Trip Coil Signature

Hydro-Québec performed first-generation of timing test by tracing curves on graduated paper film driven by a servomotor, with light deflected by mirrors fixed on galvos (current driving device). Others first-generation devices were based on oscillographic mode of record curves [11]. Most of the first generation measurements required extensive analysis based on deviation from the specifications, which suggest abnormal behavior in circuit breaker operation.

The second-generation of timing test utilized all the modern technologies in capturing the details of both analog and digital signatures. It started around 1988 and stayed on until 1995 with the introduction of microprocessor technology and digital data development. As the result, the data could be assessed and processed in digital form. Hence, it made the computation as well as the analysis became so quick and accessible. The advancement of digital data storage capacity enabled the timing test to be more practical and manageable from the perspective of operation and maintenance.

S.Bettie [12] introduced the "Profile System", which is a timing test system manufactured by Kelman Ltd. The commercial product is designed to capture associated signal data that relates to "First Trip Test" of Circuit Breaker for MV switchgear. As compared to normal and typical trip test, the "First Trip Test" is normally emphasized after having the circuit breaker is set for tripping purpose in its actual field function. It is due to its true reflection of the actual performance of circuit breaker in the event of functional tripping operation. The associated data are DC voltage, trip coil signature and main contact. The analysis of the trip coil signature depended on the human interpretation based on technical expert's experience. The device is specifically designed for quick measurement and analysis at site. The application of the product was reported by R.Henderson [2] and R. Speed [13]. The evolution of the commercial product is noted along with the change of manufacturer.

Hydro-Québec also evaluated and approved a few timing test systems, including Model CBA-32P from Zensol Automation used in Québec City area [10]. Unlike the previous design from Kelman Ltd, the model from Zensol is equipped with additional testing feature in measuring travel, velocity and acceleration of main contacts. In addition, it also measures the speed damping characteristics as well as pressure and temperature measurements [14]. Another model from Vanguard is also equipped similar capabilities in measuring mechanical performance of circuit breaker [11]. CIBANO 5000 from Omicron is another timing test system that has additional capability in measuring dynamic contact resistance testing in order to detect signs of wear and tear on the main and arcing contacts.

At the transmission level, trip coil signature can be measured by using substation Digital Fault Recorders (DFR). However, the analysis of synchronous data requires a specific application and expertise, which focus explicitly on the timing data in real-time. It is mostly useful in assessing the performance of equipment integrity in transmission level.

In summary, the trip coil signature can be easily acquired by using the measurement techniques as in TABLE I. The measurement techniques are simplified with the Digital Signal Processing (DSP) applications that are found in most of testing equipment nowadays.

TABLE I. MEASUREMENT TECHNIQUE USED TO OBTAIN TRIP COIL SIGNATURE

Level	Test Condition	Processing Type	Example
Distribution	Online/ Offline	Asynchronous	1st and 2nd Generation of Timing Test Set
Transmission / Generation	Online	Synchronous	Digital Fault Recorder (DFR)

B. Analysis Technique

In the early introduction of trip coil signature under timing test, the analysis were made by expert who had vast experience in dealing with different pattern of trip coil signature. Therefore, the analysis results are normally very subjective and inconsistent.

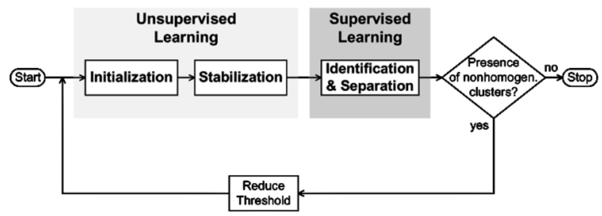

Figure 4. Neural network training using combined unsupervised and supervised learning

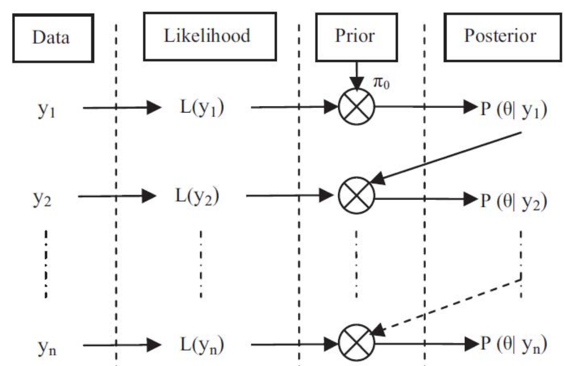

Figure 5. Sequential Bayesian approach

As shown in Fig. 4 and Fig. 5, M.Kezunovic et al applied a trained Artificial Neural Network (ANN) [15] [16] and Bayesian approach [17] to recognize patterns of transmission line faults to be incorporated in a PC-based system, which analyzed data files from substation Digital Fault Recorders (DFR). The neural network was able to detect abnormal condition and subsequently classified the data into four criteria. Subsequently, M.Kezunovic et al [18] established the Expert System, which incorporated all possible 99 rules, including the description of the circumstance that will activate the rule, a list of related signal parameters, thresholds, limited scope of the rule and an output statement. Eventually, solution software was introduced and called "Circuit Breaker Monitoring and Analysis" (CBMA) [19] [20]. The 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. Further analysis was carried out by establishing a probabilistic maintenance model of circuit breaker [21] [22] [23] [24] [25]. M.Kezunovic et al introduced a new practical methodology that used condition monitoring data to establish circuit breaker operational health assessment. It helped to identify the transmission lines, which were available for switching actions from perspective of circuit breaker reliability [26].

Another method in analyzing the trip coil signature was established by applying a data driven approach to the condition assessment of distribution circuit breakers, in which the trip coils signature data was captured from a population of in-service circuit breakers during routine trip testing. Strachan et al [27] [28] implemented a prototype system in assessing the condition of distribution circuit breakers based on a pilot study conducted on a population of 600 units of MV circuit breakers, which were in service within SP Power Systems, UK. The system has the capability to analyze the trip coil signatures, and it comprises of several sub-systems in serial process, namely data preparation, data visualization and data analysis. Under data preparation, the system used several feature vectors to characterize the trip signature and discriminate between different aspects of breaker operation and condition. The feature vectors are Latch Time, Buffer Time, Main Contact Time, Auxiliary Contact Time, End Time and Current Ratio. These feature vectors were later translated into six-dimensional (i.e. six features) Euclidean space by using Sammon Mapping [29]. Subsequently, K-Means clustering algorithm [30] mapped onto the initial Sammon map as shown in Fig. 6, where the different K-Means clusters are represented by points of different shapes.

Another prototype system in analyzing the trip coil signature was introduced by Peilei Rao et al [31]. This system, which comprised of both hardware and software, was developed based on characteristics of trip coil signatures for tripping and closing operation of circuit breakers. It used discrete-time Mallet wavelet transform algorithm to process the signal of coil current. At the end of system, it was capable to detect abnormal condition based on time discrepancy. The system was applied on a population of circuit breakers installed in Changchun substation pin China.

H. Johal and M. J. Mousavi [32] proposed to use six different transitional time regions (i.e T1, T2 etc.) that are associated with the change points in trip coil signature in order to characterize the circuit breaker condition as shown in Fig. 7. The algorithm was based in time domain approach, and it subsequently tried to detect any deviation or so-called local extrema within each individual transitional time region.

A. A. Razi-Kazemi et al [33] [34] [35] presented a new predictive methodology in analyzing the trip coil signature for tripping and closing operation of circuit breakers. The perspective of the analysis was focused to the failures and its causes. Based on a set of investigation results, a new set of a failure detection algorithm using trip/close coil signature was developed. The methodology was applied on a population of circuit breakers with 72.5-kV and 24-kV rating voltages using SF_6 insulation medium and using a spring-drive mechanism. There are six (6) features used in failure detection algorithm as shown in Fig. 8. The Failure Detection Algorithm (Fig. 9 and Fig. 10) is also developed to facilitate the analysis associated with patterns identified by identified features.

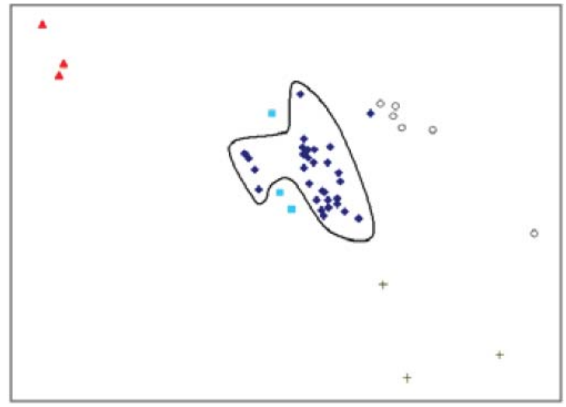

Figure 6. K-Means clustering algorithm and Sammon map of trip signature feature vectors.

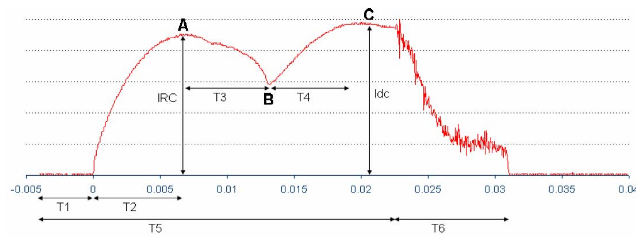

Figure 7. Transitional time regions used to characterize the circuit breaker condition

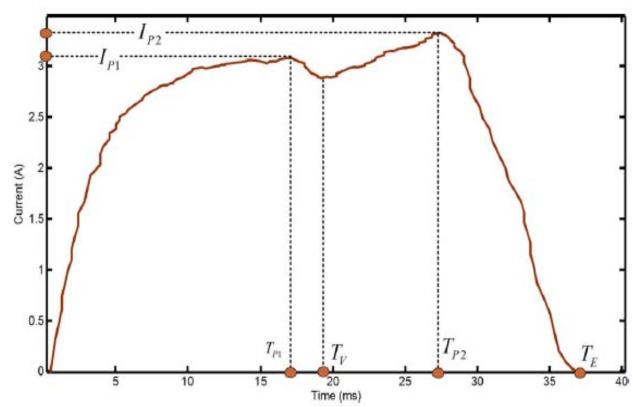

Figure 8. Six (6) features are used in failure detection algorithm.

1) I_{P1} - first peak current
2) T_{P1} - excitation time
3) I_{P2} - second peak current
4) T_{P2} - auxiliary contact operation time
5) T_V - start time of CBs operation (latching time)
T_E - total energizing time of Coil Current

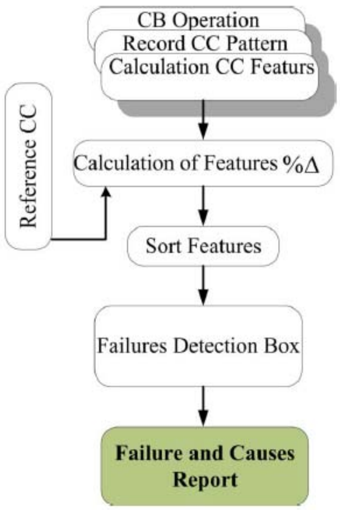

Figure 9. Failure detection algorithm using trip/close coil signature

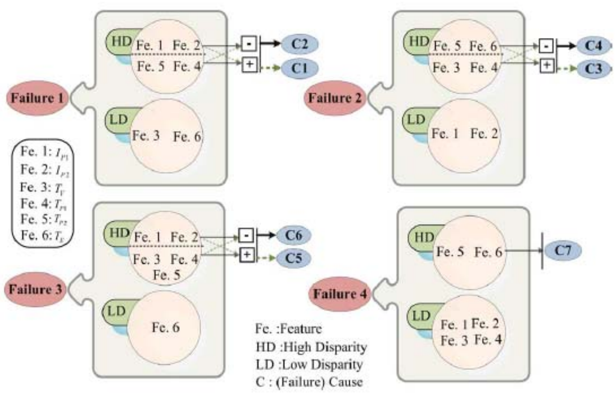

Figure 10. Failures detection algorithm box

Another analysis technique was introduced by Saugata S Biswas et al [36] with the combination of mechanical, electrical and temperature factor. Based on the real-time data, the trip coil signature is analyzed using a mathematical analysis based on slope detection throughout trip coil signature, which computes the real-time data and predictive health condition of the circuit breaker along with the relevant recommended maintenance actions. Up to this date, researchers tend to find new analysis technique in dealing with trip coil signature in circuit breaker. In this paper, the discussion on available analysis technique of trip coil signature is summarized as in TABLE II.

IV. Conclusions

In this paper, the research development in analyzing the trip coil signature for circuit breakers is discussed. With the enhancement of modern digital measurement, the trip coil signature can be analyzed from various perspectives in order to assess the functional condition of circuit breaker, which is to detect a fault condition and to isolate an electrical system in the event of overload or short circuit. The current research in analyzing trip coil signature is mainly focusing on the test result obtained at a particular time or instantaneous time frame. Under Condition-based Maintenance (CBM) practice, the maintenance engineers in the field normally use the current trip coil signature of a circuit breaker and compare it with the previous trip coil signature of the same circuit breaker. The main objective in making such comparison is to identify any abnormal pattern in trip coil signature that might be associated with potential root cause of failure. The iterative process of obtaining and comparing the trip coil signature should be simplified and replaced with appropriate algorithm, which focuses more on data trending analysis. With suitable data trending analysis, more relationship can be established between the trip coil signature and potential failure in circuit breaker. However, the process of data trending analysis is very extensive and requires enormous database of trip coil signature data for circuit breaker.

Another challenge in circuit breaker analysis is the uniqueness of the trip coil signature for every respective designs of operating mechanism by different manufacturers which requires a very detailed scrutiny. These challenges should be tackled respectively in a strategically manner with the support from various switchgear manufacturers and power utility company. With the actual data collected during operation and maintenance period, we collectively are able to build up a huge database of trip coil signature for analysis.

In most of failure cases related to tripping malfunction in switchgear, it normally would happen after the switchgears have been operated in the network. Thus, the historical data trending analysis of trip coil signature may hold the answer in identifying the root cause of failure in switchgear tripping mechanism. In previous research work, there were some elements of historical data analysis used in the methodology. However, there should be a dedicated set of trip coil signature, which is established as reference database and is reflected to respective failure pattern in circuit breaker. With complete understanding of failure pattern identification through suitable historical data trending process, we are able to take necessary prevention measures in order to ensure smooth operation of switchgear in the network. Perhaps, a balance analysis approach, which comprises of historical data trending analysis and failure pattern recognition analysis, is anticipated for more accurate investigation of trip coil signature for circuit breaker. By having this approach, we are able to monitor the progression of switchgear performance throughout its lifetime. It may also take care of the wear-and-tear issue in mechanical parts, which should resemble the lifetime assessment of mechanical parts used in automotive vehicles.

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TABLE II. ANALYSIS TECHNIQUE OF TRIP COIL SIGNATURE

Name of Researcher	Methodologies	Identification Process	Application Level
M.Kezunovic	Artificial Neural Network (ANN) and Bayesian approach to recognize fault pattern in transmission system.	Diagnostic	Transmission
Strachan	Sammon Mapping and K-Mean Clustering.	Diagnostic	Distribution
Peilei Rao	Discrete-time Mallet wavelet transform.	Diagnostic	Transmission/ Generation
H. Johal and M. J. Mousavi	*Local extrema* detection	Diagnostic	Distribution/ Transmission/ Generation
A. A. Razi-Kazemi	Failure detection algorithm that associates its cause of failure during tripping and closing operation of circuit breakers.	Prognostic	Distribution
Saugata S Biswas	Slope Detection throughout Trip Coil Signature	Diagnostic and Prognosis	Distribution/ Transmission/ Generation