A Model-Based Fault Detection Framework for Vacuum Circuit Breaker by Trip Coil Analysis

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Abstract—Vacuum circuit breaker becomes more and more complicated, integrated, high-speed and intellectualized. To insure vacuum circuit breaker in its good conditions, the function of fault diagnosis gets more important than before in the process of repairing. This paper is addressed a model-based fault detection framework for vacuum circuit breaker by trip coil analysis. At first, the electromagnetic model of the trip coil is built. Secondly, algorithm of abrupt changes detection and dynamic time warping algorithm is introduced. At last, value comparison between the similarity and the threshold concludes whether a fault has occurred or the trip coil has potentially hazardous effects. The experimental results show that this method is effective.

Index Terms—Vacuum Circuit Breaker (VCB), Fault Diagnosis, Dynamic Time Warping (DTW)

I. INTRODUCTION

Circuit breakers must be fully operational and available at all times. Now circuit breakers are the important system protection assets which should be in condition assessment and performance monitoring. Therefore, any risk of dangerous situations could be surely reduced. In such complex system of vacuum circuit breaker, fault diagnosis plays a vital role. A fault in a system will lead to economic losses. Therefore, fault diagnosis must be done correctly and efficiently. Fault diagnosis is performed when a vacuum circuit breaker is malfunctioning and is to determine the cause responsible for a set of observed symptom [1-3]. One practical predictive maintenance approach is based on the trip coil current. The trip coil is an electromagnetic actuator which when energized causes an armature to strike and release the trip latch. It can be seen therefore, that while current flowing through the coil affects a force upon the armature, the movement of the armature through the coil generates an electromagnetic field in the coil, which in turn has an effect upon the current flowing through it [4]. The method identifies the critical time instants in the trip coil current, to be used for diagnostic analysis [6-7]. The shape of the coil current characterizes the operating health of the breaker to a greater extent. The shape is influenced by both the electrical parameters of the control circuit and the mechanical movement of the armature. The characteristic behavior of the trip coil in a circuit breaker must be analyzed and modeled before the trip coil can be predictive maintenance. [8-10]

We address a model-based fault detection framework for vacuum circuit breaker by trip coil analysis in this paper. At first, we build the electromagnetic model of the trip coil. Secondly, we introduce the algorithm of abrupt changes detection to get the key points and the DTW algorithm to compute the similarity value of the trip coil current between the test data and the theoretical results. At last, if the similarity value is larger than the threshold value, comparison concludes that a fault has occurred or the trip coil has some potentially hazardous effects. The results of experiment show the diagnosis methodology is accurate and reliable. Such a model-based fault detection framework helps to increase the reliability and availability of the vacuum circuit breaker by reducing the number of shutdowns that are necessary for systematic maintenance.

II. THE DYNAMIC MODEL OF TRIP COIL

The electrical schematic of the ideal trip coil is given in Fig.1. The trip coil has an inductance $L(x)$ and a resistance $R$. The voltage $u$ applied to the coil results in a current $i$ governed by the differential equation [3-4]. The trip coil has an inductance $L(x)$ and a resistance $R$ in series. The voltage $u$ is applied to the coil results in a current $i$ governed by the equations (1)-(4). The dynamic model of the trip coil in a vacuum circuit breaker is presented by means of solving these functions. Table 1 is these variables in representation.
Figure.1 An electrical schematic of the ideal trip coil.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Variables Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x)</td>
<td>an effective displacement of the armature</td>
</tr>
<tr>
<td>(L(x))</td>
<td>inductance of the trip coil with the armature displacement (x)</td>
</tr>
<tr>
<td>(R)</td>
<td>resistance of the trip coil</td>
</tr>
<tr>
<td>(i)</td>
<td>the trip coil current</td>
</tr>
<tr>
<td>(u)</td>
<td>supply voltage of the trip coil</td>
</tr>
<tr>
<td>(m)</td>
<td>mass of the armature</td>
</tr>
<tr>
<td>(k)</td>
<td>coefficient of the spring rigidity</td>
</tr>
<tr>
<td>(F_e)</td>
<td>electrodynamic force of the trip coil</td>
</tr>
<tr>
<td>(v)</td>
<td>the armature velocity</td>
</tr>
<tr>
<td>(a)</td>
<td>the armature acceleration</td>
</tr>
<tr>
<td>(f_0)</td>
<td>the friction force of the armature movement</td>
</tr>
<tr>
<td>(t_0)</td>
<td>the time when supply voltage (u) being applied</td>
</tr>
<tr>
<td>(t_1)</td>
<td>the time when the coil current starts rising</td>
</tr>
<tr>
<td>(t_2)</td>
<td>The time that end of armature movement</td>
</tr>
</tbody>
</table>

The balance equation of forces acting on the armature of a mass \(m\) is as follows:

\[
F_e - kx - f_0 = m \frac{dv}{dt} \tag{2}
\]

\[
F_e = \frac{1}{2} \frac{di}{dt} \frac{dL(x)}{dx} \tag{3}
\]

\[
\frac{dx}{dt} = v \tag{4}
\]

The simulation of the close coil is performed by means of the Matlab 2012 with Simulink(Fig. 2). A simulation model is made in Simulink basing on Equ.1-Equ.4. This model is used to simulate the mathematical model of the close coil. The simulation results in obtaining time curves of the coil current \(i\). The course of current \(i\) changes over time displays the way in which the electromagnetic force of the coil is controlled. The simulation curve is shown in Fig.3.

III. A MODEL-BASED FAULT DETECTION FRAMEWORK

The problem of fault detection for a trip coil in VCB involves two aspects. Firstly, the detection of failures should be achieved. Secondly, the detection of smaller faults, which affect a trip coil without causing it to stop. And this is also required to prevent the subsequent faults. Both faults and failures in a trip coil can be approached in the abrupt change detection [11-12]. Algorithm of abrupt changes detection is the core of the fault detection framework.

Algorithm of abrupt changes detection is a powerful new tool for determining whether a change has taken place. It is capable of detecting subtle changes by three steps, which are data smoothing, change-point detection, and potential hazards detection. Data smoothing is used to eliminate "noise" and extract real trends and patterns of the trip coil current. Change-point detection is to discover time points at which properties of the trip coil current change. Finally, potential hazards detection is to scan for potential hazards of the trip coil and accidents in a vacuum circuit breaker can be avoided.

A. Data Smoothing

An input sampling sequence of the trip coil current with a fixed sampling rate is \(i = \{i_1, i_2, \ldots, i_t\}\). Data smoothing produces a "smooth" set of values from the
trip coil current which has been contaminated with noise. The LOWESS smoothing is introduced in this abrupt changes detection. LOWESS smoothing is an improvement over least squares smoothing when the data are not equally spaced. The following is a brief sketch of improvement over least squares smoothing when the data changes detection. LOWESS smoothing is introduced in this abrupt change points, the set of Euclidean distances among all extrema and the other accounting for common extrema information as the feature vector. To reduce the change points, the set of Euclidean distances is computed. To do this, we use Golden Section Search, which is an elegant and robust method of locating all extrema in trip coil current data. To find the best match between these two sequences, we retrieve a path through the matrix that minimizes the cumulative total distance between them. In particular, the optimal path is the path that minimizes the warping cost.

C. Dynamic Time Warping Fault Detection

Dynamic time warping (DTW) is an algorithm for measuring similarity between two sequences which may vary in time or speed. DTW has been applied for the data which can be turned into a linear representation. And DTW can be used in partial shape matching application. For details of DTW algorithm, please see [17-18].

Suppose we have two current series, an input sequence \( Q \) of length \( n \), and a template sequence \( C \) of length \( m \), where

\[
Q = q_1, q_2, \ldots, q_n
\]

\[
C = c_1, c_2, \ldots, c_m
\]

To align these two sequences using DTW, we first construct an \( n \)-by-\( m \) matrix where the \( (i_0, j_0) \) element of the matrix corresponds to the squared distance,

\[
d(q_i, c_j) = (q_i - c_j)^2
\]

which is the alignment between points \( q_i \) and \( c_j \). To find the best match between these two sequences, we retrieve a path through the matrix that minimizes the cumulative total distance between them. In particular, the optimal path is the path that minimizes the warping cost.

\[
Path(Q, C) = \min \left( \sum_{k=1}^{K} w_k \right)
\]

Where \( w_k \) is the matrix element \((i_0, j_0)\) that also belongs to \( K_{th} \) element of a warping path, a contiguous set of matrix elements that represent a mapping between \( Q \) and \( C \).

This warping path can be found using dynamic programming to evaluate the following recurrence

\[
r(i, j) = d(i, j) + \min \{ r(i-1, j-1), r(i-1, j), r(i, j-1) \}
\]

where \( d(i, j) \) is the distance found in the current cell, and \( r(i, j) \) is the cumulative distance of \( d(i, j) \) and the minimum cumulative distances[19-21].

In this type of fault detection technique, the theoretical data is converted to templates. The diagnosis process consists of matching the test data with stored templates. A fault is detected if the distance is larger than the threshold value. The distance is based upon dynamic programming. This is called the DTW fault detection.

The implementing processes of the fault detection method are illustrated in Fig 4.
TABLE II.
CHANGE POINTS DETECTION ALGORITHM

<table>
<thead>
<tr>
<th>Step</th>
<th>ALGORITHM : Change Points Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:</td>
<td>Input:</td>
</tr>
<tr>
<td>2:</td>
<td>trip coil current ( i );</td>
</tr>
<tr>
<td>3:</td>
<td>Output:</td>
</tr>
<tr>
<td>4:</td>
<td>change points ( i_{cp} );</td>
</tr>
<tr>
<td>5:</td>
<td>Functions:</td>
</tr>
<tr>
<td>6:</td>
<td>LOWESS smoothing function: LOWESS()</td>
</tr>
<tr>
<td>7:</td>
<td>Locating all extrema function: extrema ()</td>
</tr>
<tr>
<td>8:</td>
<td>Computing Euclidean distances function: Euclidean ()</td>
</tr>
<tr>
<td>9:</td>
<td>K-Means clustering function: K-Means ()</td>
</tr>
<tr>
<td>10:</td>
<td>Algorithm:</td>
</tr>
<tr>
<td>11:</td>
<td>Smoothed Data ( r = \text{LOWESS}(i) );</td>
</tr>
<tr>
<td>12:</td>
<td>Smoothed Data extrema ( r = \text{extrema}(r) );</td>
</tr>
<tr>
<td>13:</td>
<td>Euclidean distances ( d = \text{Euclidean}(r) );</td>
</tr>
<tr>
<td>14:</td>
<td>change points ( i_{cp} = \text{K-Means}(d) );</td>
</tr>
</tbody>
</table>

IV. EXPERIMENT

The experimental system includes hardware composition and software system used for trip coil current signal acquisition and fault detection software. The system offers PC-Based oscilloscope that have the performance and features necessary to monitor trip coil current waveform data.

ACS712 is a linear current sensor. The device consists of a precise, low-offset, linear Hall sensor circuit. Applied current flowing through this copper conduction path generates a magnetic field which is sensed by the integrated Hall IC and converted into a proportional voltage. Device accuracy is optimized through the close proximity of the magnetic signal to the Hall transducer. A precise, proportional voltage is provided by the low-offset, chopper-stabilized BiCMOS Hall IC, which is programmed for accuracy after packaging. The output of the device has a positive slope when an increasing current flows through the primary copper conduction path, which is the path used for current sensing.[22]

The data acquisition platform uses DSO3064 digital oscilloscope which has 4 Channels Oscilloscope, 60MHz Bandwidth, 200MS/s sampling rate and 10k--16M memory depth. The software environment consists of Matlab and a newly developed fault diagnosis library. (Fig.5)

Figure.4 the implementing processes of the fault detection method

A. Change Points Detection Experiment

We sample the sequence of the trip coil current with a fixed sampling rate 50 kHz. The sequence is shown in Fig. 6(a). In this sequence, the true signal amplitudes changes rather smoothly as a function of the time values, whereas many kinds of noise are seen as rapid, random changes in amplitude from point to point within the signal. We attempt to reduce the noise by LOWESS smoothing. In this smoothing, the sequence of the trip coil current is modified so that individual points that are higher than the immediately adjacent points are reduced, and points that are lower than the adjacent points are increased. This leads to a smoother sequence and it is shown in Fig. 6(b).
The CPD algorithm requires the identification of all local extrema in the smoother sequence. Fig. 7 shows performance results of the algorithm for identification of extrema.

By computing the Euclidean distances between these extrema, we obtain the distance sequence shown in Fig. 8.

Cluster distance sequence into two disjoint subsets which are shown in Fig. 9. We get the key points in the sequence of the trip coil current by the change point’s subset in Fig. 10.

### B. DTW Fault Detection Experiment

This experiment presents the analysis of current signals to identify and quantify common faults from a trip coil based on DTW algorithm. Experimental data sets of normal signal and abnormal signal have been studied using DTW algorithm. We can obtain better fault detection and diagnosis results, as depicted in Fig. 11 and 12. Results show that the method is effective.
V. CONCLUSIONS

This paper summarizes the key features of the model-based fault detection framework for vacuum circuit breaker and the methodology scheme is proposed. At first, the mathematical model has been developed for the dynamic characteristics of the close coil. The results of simulation show that the accuracy of the dynamic-state model equations is satisfactory. Secondly, the algorithm of change points detection for applications in fault detection for a trip coil is presented. The algorithm includes three parts which are data smoothing, extrema search and K-Means clustering. Fault analysis processing is based on dynamic time warping technology. Thirdly, fault analysis processing is based on dynamic time warping technology and the change points detection algorithm. Experimental results prove the effectiveness of the methodology in the vacuum circuit breaker fault detection.

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