Online Monitoring of High Voltage Circuit Breaker By Multi-resolution analysis of Mechanical Component Signals

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***Abstract*—In this paper, a new solution for automated analysis of circuit breaker operation based on a record of waveforms taken from a circuit breaker test unit is presented. The Solution is implemented based on status and analog signals acquired form controlling relays and mechanical moving systems. Multi-resolution analysis is utilized to extracted waveform features and an expert system is used for circuit break fault detection. The experimental results show the robustness of the extracted features and their ability to detect faults in circuit breakers.**

Key Words: Circuit breaker monitoring, Signal Processing, Multi resolution analysis

I. INTRODUCTION

Circuit Breakers (CBs) are critical power equipments in power systems, and are utilized to change the topology of a power system in order to accommodate various configurations in routing the load. Another application of CBs is their roll in isolating a power system when faults are encountered. To this end CBs should always be ready for operation; otherwise costly consequences might be imposed. However, preventive maintenance and testing intervals are usually performed on long term intervals which may reach up to one year [1, 2]. Online Monitoring of CB is a way to assess the performance of the apparatus using event taken records and fixed intervals to record data from the device. These signal are then processed and different features are extracted from them [3-5]. Based on feature analysis it is then decided on condition of the CB [6].

The choice of signal selection mostly corresponds to the parameters of the CB which are intended to be monitored [7]. In [3] the CB travel curve characteristics were considered to diagnose the CB faults, where neural networks were utilized to recognize difference between a reference signal and the test signal. In [1] Discrete Wavelet Transform (DWT) was used to extract a series of feature form CB control signals and then an expert system was used for CB fault diagnosis. Vibration analysis has also been utilized to monitor the status of CB. [8] used a method based on the relationship of signal waveform Eigen values and circuit-breaker operating time sequence to diagnose faults of high voltage circuit breaker.

The Least Square Support Vector (LSSV) was used to extract the characteristic entropy of HV circuit breaker's vibration signals and to improve the accuracy of fault diagnosis the particle swarm optimization algorithm was adopted to optimize the parameters of LSSV algorithm [9].

Mechanical components signals of the CB hold much useful information that relates to the condition of the apparatus; but feature extraction from these signal has gained less attention due to complex signal processing requirements intended for feature extraction.

In this paper mechanical signal of the CB are considered for online monitoring of CB. The mechanical travel curve and the damping curve, along with the close/open coil current are analog signals, which hold useful information about the CB. To deal with complex signal processing required for feature extraction, Haar wavelets are utilized and from the decomposition of signal into smaller sub-bands, various features are extracted from them. Based on the rule based expert system and the features extracted from these signals the condition of the breaker is then determined.

The rest of the paper is organized as follows: section II reviews the operating mechanism of a CB, Section III introduces the proposed solution for CB monitoring and signal processing requirements are explained in section IV. In section V the experimental results are shown and the paper is concluded in section V1.

II. CB OPERATING MECHANISM

In general, the circuit breakers consist of two main parts, the poles and the mechanism. The poles consist of contact and arc-extinguishing devices. The mechanism is the part to open or close the contacts in the poles at the same time instantaneously (with max. 5 milisec. Tolerance). The closing and opening procedures are performed through springs which are charged by a servomotor and a driving lever. In the system, the closing springs are first charged. If "close" button is pressed the opening springs get charged while the contacts get closed. Thus, circuit breaker will be ready for opening. The mechanical operating cycle of the circuit breaker is (OPEN-3 Min CLOSE/OPEN-3 Min-CLOSE/OPEN) or (OPEN-0.3 sec-CLOSE/OPEN-3 Min CLOSE/OPEN). The second cycle is valid when the circuit breaker is used with re-closing relay. In that case, after the closing operation, the closing springs are charged by the driving lever or by driving motor (if equipped). Thus, the circuit breaker will be ready for opening and re-closing.

Sulfur Hexafluoride (SF6) is used in such devices since it is an excellent gaseous dielectric for high voltage power applications. It has been used extensively in high voltage circuit breakers and other switchgears employed by the power industry. Applications for SF6 include gas insulated transmission lines and gas insulated power distributions. The combined electrical, physical, chemical, and thermal properties offer many advantages when used in power switchgears. Some of the outstanding properties of SF6 making it desirable to use in power applications are: High dielectric strength, unique arc-quenching ability, excellent thermal stability, and good thermal conductivity.

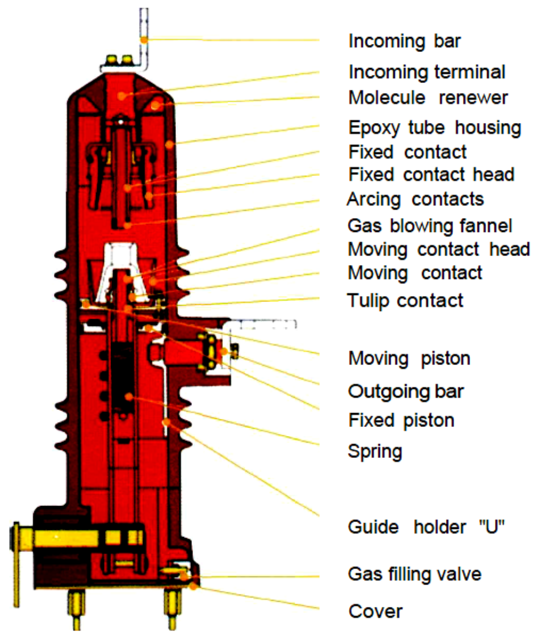

Fig. 1. CB components

III. Proposed Solution for CB Condition Monitoring

For CB condition monitoring, 3 challenges have to be faced: Signal selection, feature extraction, and decision making. Fig. 1. Shows types of CB failures by major components. As can be seen in the figure, most of failures are results of mechanical components, such as trip coils and close coils, main contacts, point of contact separation and contact touch. Electrical parameters are mostly concerned with dielectric and interrupter failures. Auxiliary control circuits are also a cause of 11% of failures.

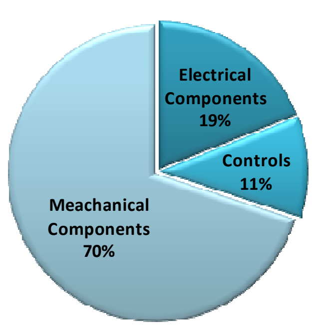

Fig. 1. Breaker failure types by major components.

Based on fig 1, the most important parameters of the CB to be monitored are the mechanical components of the apparatus. Table 1 provides a list of these components, and the element that can be measured to reveal the condition of each corresponding component. Also for a target CB, a list of expected values that show the health of the CB are also shown.

Table 1. Mechanical parameters of CB

Parameter	Measuring elements	Expected value ±20% tolerance
Charging Motors	Motor current	20A/10.5Sec
Travel distance and velocity	Contact travel curve	159mm/4.5(m/sec)
Trip coil and close coils	Coil current	42V/36V
Damping time	Damping curve	20mm/198ms
Ambient temperature	temperature	-
cabinet space temperature	Temperature	-

By measuring each element and comparing the result with the reference value, it is possible to make a statement about each component. Fig. 2 shows different steps of the proposed solution for monitoring the condition of the CB.

First signals of high importance are extracted. The current of the charging motors, and the temperatures are scalar values that are directly measured by reading the output of relative sensors; but the coil current, contact travel curve and the damping curve are analog signal that the corresponding features from these signal has the be extracted by employing signal processing methods. In this step, DWT analysis is used as the multi-resolution approach for feature extraction.

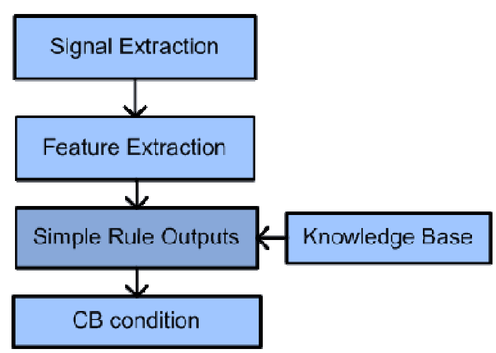

Fig. 2. Solution Architecture for CB monitoring by inspecting mechanical components

To report the condition of the CB, an expert system is used as the classifier [10] in the final step. Here a list of rules made by excepted value for each feature is built and by incorporating if-then rules, the status of the CB is reported.

IV. Feature Extraction

Three signals were found to be analog inputs, thus a feature extraction process is conducted on each one, in order to find their relative features. DWT is a multi-resolution, signal analysis method that unlike the Fourier transform can reveal the frequency content of a signal along with time display of each frequency component. Thus it is possible to extract features in different signal frequency resolutions, which also provide the features in the required time frame. In the following sub-sections the errors that each signal reveals, the representative feature, and feature extraction is explained in detail.

A. Travel Curve Signal

Contact travel curve is an easy to measure signal which provides dynamic information about the operating components of the CB. A deviation from baseline signal signature reveals a malfunction in the CB, which would require maintenance of the system. Fig 4 (a) through (b) illustrates the type faults that can be extracted from this signal.

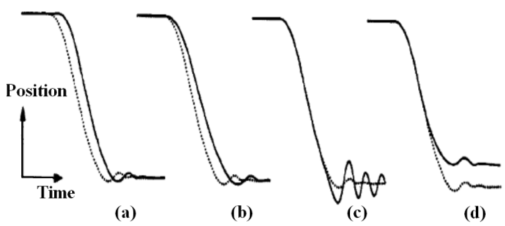

Fig. 3 Types of deviations from the original signal signature.

Fig 3 (a) indicates the contact separation has happened sooner than expected, which in turn is an indication of contact wear. Fig. 3(b) shows a faster contact stroke, which indicate that the spring mechanism has been energized more than expected. This can in turn indicate the incorrect operation of the charging motors. Fig 3(c) shows that the damping mechanism was not able to damp the system at the end of the opening operation, which shows the failure of shock observer. Fig. 3(d) shows that the total travel distance has reduced, which can be a result of insufficient energy.

Typical curves for an opening and closing operation are shown in fig 4, and for each figure the points of interest that have to extracted from each signal in order to make a decision about the condition of the breaker is also shown in this figure. These features are further listed in table 2. In order to extract these features, DWT is performed on each signal and by choosing the correct level of decomposition, the required features are extracted.

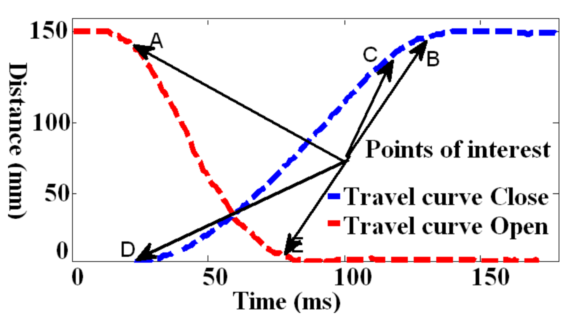

Fig. 4. Typical contact travel curves for (a) open and (b) close operation.

Table 2 Features for travel curve

Feature	Description
Op_Star (A, D)	Operation start time
Op_end (C,E)	Operation end time
movement	Displacement of the contacts
velocity	Contact movement velocity
Overshoot (B)	Effect of Damping

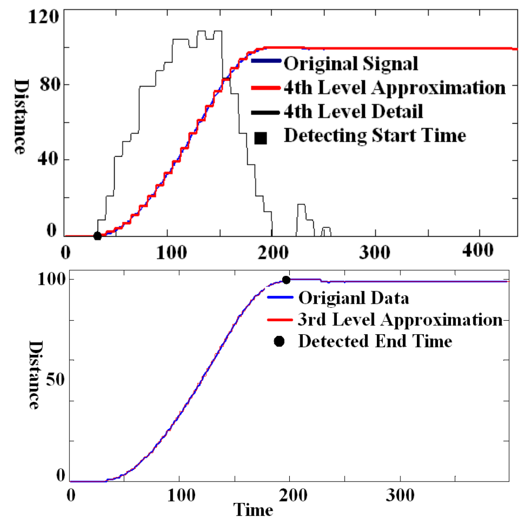

Fig. 5 Extracting point (D) and (C)

Fig. 5 shows the signal decomposition of the CB travel curve using Haar wavelets. For finding point (D) 4[th] level approximation and detail confidents are extracted. It is then found that for this signal point (D) happens on the beginning time for each coefficient greater than zero. Points (A), (C), and (E) are found in the same fashion.

The speed of the mechanism can be used by incorporating these two features as:

$$velocity = \frac{t(op\_end) - t(op\_start)}{op\_end - op\_start} \quad (1)$$

where *t* represent the distance as a function of time. The total mechanism movement can also be calculated by:

$$movement = t(op\_end) - t(op\_start) \quad (2)$$

B. Damping Curve Signal

Damping curve can be utilized to monitor the damping time and velocity. These measurements provide useful information on the health of the spring mechanism of the CB. Fig. 5 shows a typical damping curve from a spring operated 460KV CB [11].

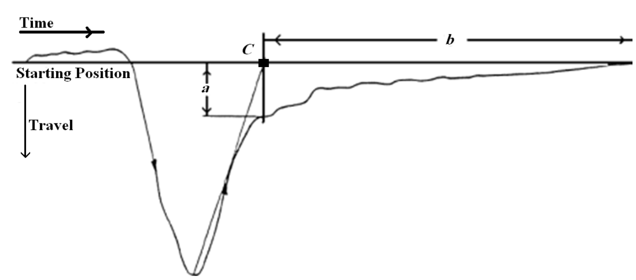

Fig. 5. CB damping curve curtsey of [11].

The two features *a*, *b* represent the damping distance and time respectively [11]. The crossing point of the tangent line on the curve with the horizontal axis (time) is used in order to find the damping time as:

$$a = d(C) \quad (3)$$

and

$$b = C - final\_position \quad (4)$$

where C is the crossing point and *final_poisiotn* is where the cam disk has reach it's destination. In order to find the parameters of the distance line, the derivative of d (the damping travel curve) is utilized. Fig 6 shows the process for extracting the tangent line.

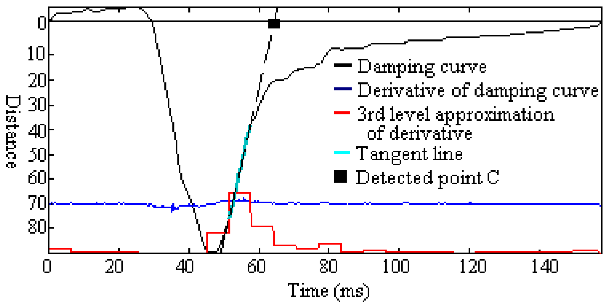

Fig. 6. Extracting the tangent line

In this process, first, the derivative of the curve is calculated and then it is de-noised by setting the 5th and 6th level, detail coefficients equal to zero.

Then by considering the largest coefficient of the 3rd level decomposition as the range where the line is tangent to the damping curve, the tangent line is extracted and the crossing point shown with a black square in fig. 6 is extracted. Using (3) and (4) it is then possible to extract features a and b.

C. Coil Current Signal

The coil current signal is a very critical parameter to monitor, since 40% of mechanical failures in the CB operation is caused by a broken coil. Other than detecting the health of the coil, the rise time, fall time and the dip on the coil current can be used to find the safe operation of the latch release and the correct sequences of the operation [11]. A typical coil current signal is shown in fig. 7.The rise time and fall time are easily calculated by:

$$T_{rise} = \underset{t(coil\ current)<1/2\max(t)}{.1*\max(coil\ current)} \tag{5}$$

and

$$T_{fall} = \underset{t(coil\ current)>1/2\max(t)}{.1*\max(coil\ current)} \tag{6}$$

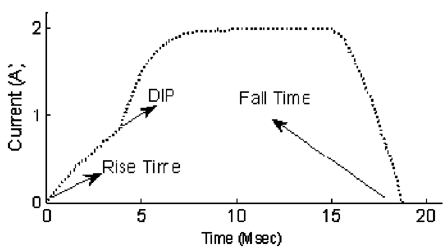

Fig. 6. Coil current curve, curtsey of [12]

In order to find the DIP on the curve, once again, wavelets are utilized, and by inspection of different decomposition levels the correct level of approximation and detail decomposed coefficients are extracted.

For this signal, it is found that the DIP in the coil currents happens in an interval with highest coefficients, and when 5th level data are utilized, the largest coefficient with the range of larges approximation coefficients indicates the place of the DIP in the coil current. The extract time of the DIP is expected to be in a certain range (4 ms after even initiation order [12]. By extracting the features explained previously, along with scalar measurements it is then possible to decide on the condition of the apparatus. The simple rules extracted upon extraction of features of mechanical signals is listed in table 3 (This is only a part of the complete rules list).

Table 3 Extracted rules

Rule	Description
R101	opening start time normal
R102	opening start time premature
R103	opening start time delayed
R104	opening end time on time
R105	opening end time premature
R106	opening end time delayed
R107	opening mechanism velocity increased
R108	opening mechanism velocity decreased
R109	opening contact movement increased
R110	opening contract movement decreased
R111	opening overshoot increased
R112	opening overshoot decreased
R113	closing start time normal
R114	closing start time premature
R115	closing start time delayed
R116	closing end time on time
R117	closing end time premature
R118	closing end time delayed
R119	closing mechanism velocity increased
R120	closing mechanism velocity decreased
R121	closing contact movement increased
R122	closing contract movement decreased
R123	closing overshoot increased
R124	closing overshoot decreased
R125	damping time increased
R126	damping time decreased
R127	damping distance increased
R128	damping distance decreased

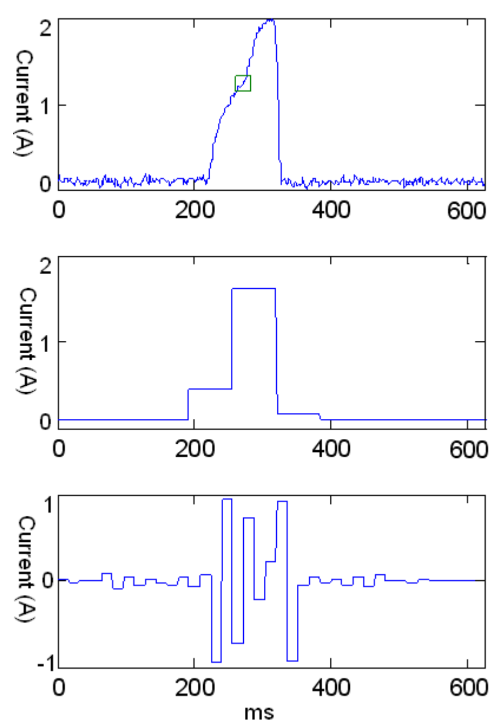

Fig. 7. Decomposition of coil current using DWT

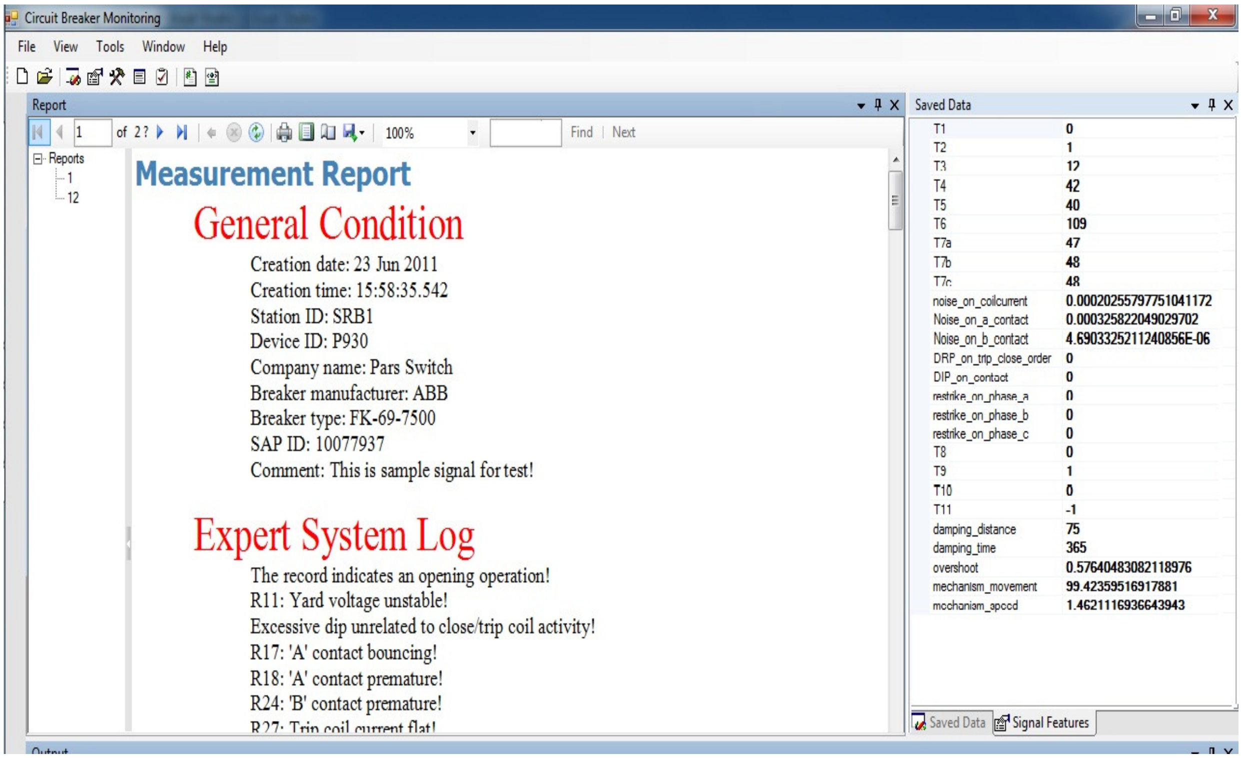

Fig. 9. An overview of the Reporting software

V. Experimental Results

In order to evaluate the effectiveness of the proposed method for CB monitoring, 169 signal signatures were collected, curtsey of Pars Switch Inc. These signals consist of 54 faulty and 115 correct signals. Fig. 8 shows a sample of a faulty contact travel curve.

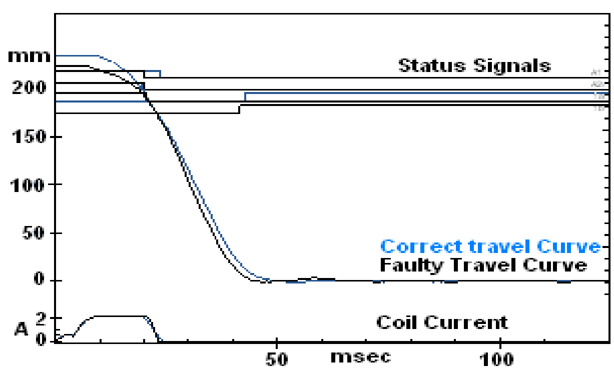

Fig. 8. A sample of a faulty travel curve signal in comparison to a correct signature [12].

For this signal the total movement time of the signal is decreased which indicates possible contact wear. The total movement of the signal is calculated by (2) and Rule (R107) is found by the expert system. In the final repot on the CB status, a line indicating "Possible contact wear" is printed out. Fig. 9 shows an overview of the reporting system, where each fault on the system is reported after the Expert System Log and the rule that have caused the error are reported in the following lines. For example, the excessive dip on the coil current signal is a result of bad contact separation.

In order to find out the effectiveness of the method for detecting errors on the travel curve, table 4 summarizes the results of correct fault detections. In this table, faults are divided based on the four errors mentioned in section 3.1.

For each type of error, the number of true correct and faulty signals and the True Positive Rate (TPR) percentage is shown in table.

Table 4. Error detection in travel curve signal

	Correct		Faulty		Total
	Total	TPR	Total	TPR	(%)
Contact Wear	125	100	44	97	98.3
Spring mechanism	131	100	38	99	99.9
Shock observer	160	100	9	88	99.9
Insufficient energy	155	100	14	85.7	98.8

Based no the results of this table it can be seen that the proposed features are very reliant for detecting travel curve faults. Also from the number of faulty signals it can be implied most of the errors detected using the travel curve are caused by the contact wear and spring mechanism. An early verification of such error will lead to large cost savings, due to discovering when a component in the system needs maintenance.

Table 5 shows the result of error detection on the damping curve. These results also show that the number of errors on the damping curve is much less; which is mostly due to lesser components involved in the damping mechanism.

Table 5. Error detection using damping curve

	Correct		Faulty		Total
	Total	TPR	Total	TPR	(%)
Damping time	162	100	7	100	100
Damping distance	151	100	18	94.4	99.4

Table 6 summarizes the results of correct detection of faults on the coil current system. Excessive DIP, which indicated possible friction on the trip coil assembly, showed that this component needed more attention. In 97% of the cases, the proposed monitoring system was able to report the status of the apparatus correctly. In the collected signals, no broken coil signal was available.

Table 6. Error detection using coil current

	Correct		Faulty		Total
	Total	TPR	Total	TPR	(%)
Excessive DIP	120	98.3	49	93.8	97
Broken Coil	169	100	0	-	100

VI. CONCLUSIONS

In this paper, a new method for CB online monitoring, utilizing the mechanical signatures of the CB was proposed. For each signal relative features that each one was corresponding to a particular fault in the CB was extracted. In order to extract the features, DWT analysis was conducted. The results tested on 169 CB signals collected from the high voltage spring operated CBs manufactured by the Pars Switch Inc. showed the extracted features were effective for CB online monitoring and high accuracy in detecting CB faults showed the reliability of the method for practical applications.

REFFERECNE

[1] M. Kezunovic, et al., "Automated monitoring and analysis of circuit breaker operation," Power Delivery, IEEE Transactions on, vol. 20, pp. 1910-1918, 2005.

[2] X. Zhang, et al., "Life management of SF6 circuit breakers based on monitoring and diagnosis," Electrical Insulation Magazine, IEEE, vol. 25, pp. 21-29, 2009.

[3] M. Adam, et al., "The analysis of circuit breakers kinematics characteristics using the artificial neural networks," WSEAS Transactions on Circuits and Systems, vol. 8, pp. 187-196, 2009.

[4] F. Yang, et al., "A Novel On-line Monitoring Method for Three Phase Synchronization of Medium Voltage Vacuum Circuit Breaker," Proceedings of the CSEE, p. 12, 2008.

[5] M. Knezev, et al., "Automated circuit breaker monitoring," in Power Engineering Society General Meeting, Tampa, FL 2007, pp. 1-6.

[6] Z. Tang, et al., "Study for mechanical condition evaluation and diagnosis methods of high voltage circuit breaker," Guilin Dianzi Keji Daxue Xuebao, vol. 31, p. 123, 2011.

[7] C. Sweetser, et al., "Strategies for selecting monitoring of circuit breakers," Power Delivery, IEEE Transactions on, vol. 17, pp. 742-746, 2002.

[8] J. X. Zhong, et al., "Exploration and Practices of Mechanical State Diagnosis and Monitoring Techniques for High Voltage Circuit-breaker," High Voltage Apparatus, vol. 47, pp. 53-60, 2011.

[9] R. Jia, et al., "Application of particle swarm optimization-least square support vector machine algorithm in mechanical fault diagnosis of high-voltage circuit breaker," Dianwang Jishu/ Power System Technology, vol. 34, pp. 197-200, 2010.

[10] B. Liu, et al., "An Object Frame Knowledge Representation Approach for Fault Diagnosis Expert System," in Future Computer Sciences and Application, Hong Kong, 2011, pp. 74-77.

[11] ABB, "Setting And Checking Of Operating Of Cetain Components Of Operating Devices: BLG 20., 30., 35 And In Applicable Of BLG 10," 2008.

[12] P. Switch, "Routin test of SF6 circuit breaker," Zanjan2011.