IEEE Transactions on Power Delivery, Vol. 3, No. 4, October 1988

MECHANICAL FAILURE DETECTION OF CIRCUIT BREAKERS

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Abstract - The evaluation of the mechanical condition of a circuit breaker, i.e., whether the unit is in normal or abnormal condition, has been successfully carried out through the application of noninvasive diagnostics, together with signal processing and decision-making techniques. Through the methodology, quantitative (numerical) assessment of a circuit breaker for any operating condition has been achieved. In this EPRI and NYSERDA project, tests of oil (principally) and sulfur hexafluoride circuit breakers, involving operations under normal and abnormal conditions, were carried out at three manufacturers and at the University at Buffalo. In all cases, the presence of abnormalities was detected.

INTRODUCTION

It is well-known that malfunctions of a mechanical nature are a principal cause of failures that occur during operation of a circuit breaker [1]. Noninvasive diagnostics, through which the mechanical condition of a unit could be determined, would, then, play an important role in improving the operating reliability of a circuit breaker. In addition, the successful application of such diagnostics would lead to significant extension of the intervals for inspection and maintenance.

Two major objectives are incorporated in the present program. One thrust involves the development and application of the diagnostics--including acquisition of the vibration data, signal processing, and decision-making. The methodology developed leads to the quantitative assessment of the mechanical condition, thereby permitting the determination of whether a circuit breaker is in normal or abnormal condition. As described in the paper, the techniques have been successfully applied over a range of abnormalities and circuit breakers.

The second principal component is associated with the development of a portable diagnostic unit that can be employed in the field. The diagnostic unit is designed to acquire the test data of a circuit breaker and to carry out rapidly the signal processing and decision-making programs. The results of this task will be incorporated in a following paper.

Experiments have been conducted upon circuit breakers rated at and above 115 kV. Interrupting media have been oil (principally) and sulfur hexafluoride (SF_6). Tests have been carried out in manufacturers' laboratories, in the field at various cooperating electric utilities, and upon a unit located at the University at Buffalo. Test sites at the manufacturer and at the University offer the capability of readily imposing abnormalities under controlled conditions. Field data were often obtained during scheduled maintenance periods; here the database was constructed and enlarged. As anticipated, the presence of abnormalities during tests in the field occurred on a random basis. All signal processing and decision-making diagnostics reported in the present paper were carried out at the University.

The test results have demonstrated that certain abnormalities, e.g., a deactivated shock absorber, yield vibration signatures that are readily distinguished from their normal counterparts. Many abnormalities, however (e.g., eroded contacts), produce changes in signatures that are difficult to detect by observation. Thus, the signal processing and decision-making procedures developed in this program are necessary in order to enable consistent--and correct--determinations of the mechanical condition of a circuit breaker.

The following section describes the experiments and the diagnostic instrumentation. Signal processing and decision-making procedures are then briefly described. Finally, applications to a number of test configurations at the manufacturers' laboratories and at the University at Buffalo are presented.

A project of this scope requires the support and participation of a broad segment of the community. Direct participation as team members has included the electric utilities: New York Power Authority, New York State Electric and Gas Corporation, and Niagara Mohawk Power Corporation. Co-operative participation has included manufacturers: BBC Brown Boveri, Inc. (Greensburg, PA); McGraw-Edison Power Systems, Cooper Industries (Canonsburg, PA); and Siemens Energy and Automation, Inc. (Jackson, MS).

TESTING

Test Program

Vibration signatures have been acquired from circuit breakers having ratings of 115 kV and above. Tests have been conducted upon (principally) oil and SF_6 units. The measurements have been carried out

88 WM 222-2 A paper recommended and approved by the IEEE Switchgear Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1988 Winter Meeting, New York, New York, January 31, - February 5, 1988. Manuscript submitted August 31, 1987; made available for printing November 17, 1987.

under field conditions (at the electric utilities) and in the laboratory (at the manufacturers and at the University at Buffalo). In all cases, the circuit breakers were operated out of service.

The development of signatures and diagnostic procedures was based upon comparisons of external tank wall acceleration data obtained from a given circuit breaker that was operated under both normal and abnormal conditions. Abnormal conditions have included deactivated shock absorbers, eroded contacts, misaligned bushings, overtravel stop misadjustments, broken stationary contact, and changes in tailspring settings.

Field tests were performed before and after scheduled maintenance operations. These tests have proven useful in the development of procedures that were compatible with maintenance operations. As anticipated, abnormalities in the condition of a unit occurred on a random basis. The various field tests have provided statistical databases on (1) seasonal variability of acquired signatures from a selected circuit breaker, (2) sensitivity of response to changes in transducer location, and (3) the similarity in the signatures of different units of a given model. These aspects will be included in a following paper.

Experiments conducted at manufacturers' sites and at the University at Buffalo have permitted the introduction of abnormalities in a controlled manner (in addition, of course, to operation under normal conditions). Further, in the development of the diagnostic procedures, measurements could be (and were) obtained relatively conveniently both inside and outside of a unit. In particular, at the University at Buffalo, this arrangement has enabled extensive measurements to be carried out concerning the effects of transducer placement upon (1) the associated capability of detecting abnormalities and (2) the detailed vibrational characteristics of the transmission path from the interior (i.e., the source) to the external measurement locations used for diagnostics.

Instrumentation

An overview of the instrumentation and analysis system is presented in Fig. 1. During both laboratory and field tests, one or more accelerometers were mounted on each pole of a circuit breaker. The accelerometers were usually Kistler Model 8624 units having a nominal operating range of 0 to 500 g and 1 to 8000 Hz. Signals from the signal conditioning amplifiers were recorded on a Honeywell 5600E 28-channel FM tape recorder. Trip and close command signals were recorded simultaneously with the vibration data for timing purposes. The bandwidth of the acceleration data was approximately 0 to 8 kHz; a sampling rate of 32 kHz was generally used. Measured wall acceleration peak amplitudes ranged from less than 10 g to more than 1000 g, depending upon the type of circuit breaker and upon the measurement location. The accelerometers, therefore, had to be firmly mounted; a high-strength adhesive, in combination with a rare earth magnet, was employed. [A stud mount would have been suitable for the applications discussed in this work.]

The recorded data were then digitized and stored using a 16-channel computer-aided test system (GenRad Model 2515). Preliminary examination of the raw data was carried out using this unit. The unit was then linked to a DEC VAX 785 minicomputer for which signal processing and decision-making software has been developed.

Sample Data

Sample data from four circuit breakers are considered. The units are designated herein as: Siemens (BZO-121; 115 kV oil), General Electric (FHK-239; 115 kV oil), McGraw-Edison (RHF-90; 242 kV oil), and BBC (PA-40; 242 kV SF_6). The Siemens, McGraw-Edison, and BBC circuit breakers were new units; each was tested at the facilities of the respective manufacturer. The General Electric circuit breaker was installed and tested at the University at Buffalo.

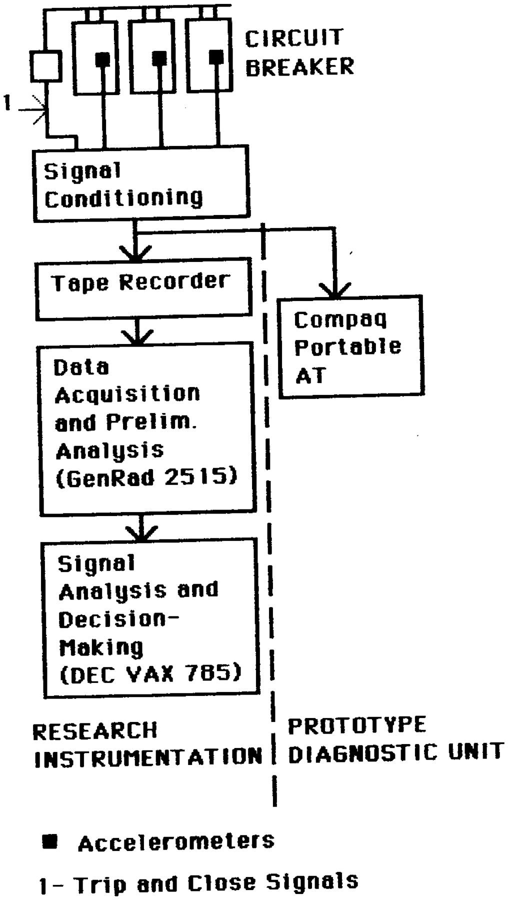

Fig. 1. Instrumentation.

External acceleration signals obtained at the top of the tank of pole 3 of the Siemens circuit breaker, during various trip operations, are illustrated in Fig. 2. Specific events occurring during operation of the circuit breaker are identified in the top trace, Fig. 2a (normal condition). The timing of particular events can be ascertained from a knowledge of the circuit breaker operation or from motion analyzer data. Changes in the signatures--between operations under normal conditions and those having abnormalities--are associated with defects. For example, changes in the signature due to (1) a shortening of the toggle between poles 2 and 3, (2) an overcompression of the tailspring, and (3) combination of eroded contacts, misaligned contacts, and deactivated shock absorber, can be seen in Figs. 2 b, c, and d, respectively. Some of these changes (from the normal signal) are quite obvious by even cursory examination of the raw data, (e.g., Fig. 2d); other changes (Figs.

2b and 2c) are more subtle, requiring the signal processing that will be discussed in the following section.

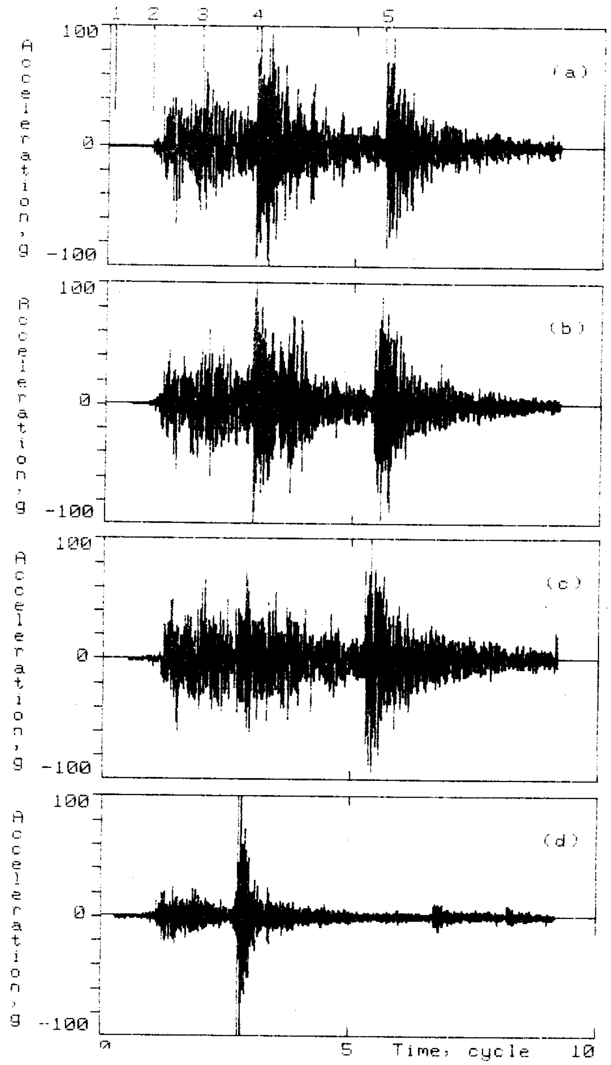

Fig. 2. Wall acceleration signals during trip operation. Siemens BZO-121 circuit breaker; 115 kV oil. (a) Normal; (b) shortened toggle; (c) overcompressed tailspring; (d) combination of eroded contacts, misaligned contacts, and deactivated shock absorber. Events: 1. trip signal, 2. motion starts, 3. contacts separate, 4. tailspring separates from base, 5. shock absorber impacted.

Figure 3 illustrates, for the General Electric circuit breaker, the contrasts between a deactivated overtravel buffer spring (Fig. 3b), a deactivated shock absorber (Fig. 3c), and the normal condition (Fig. 3a) [for trip operation]. The measurements were obtained at the top of the tank of the pole upon which the abnormalities were introduced. The absence of the shock absorber (Fig. 3c) can be clearly seen from the time traces of the wall acceleration. The deactivated buffer spring (Fig. 3b), however, produces much smaller changes in the vibration signature. Thus, there is clearly a need for signal processing in order to be able to render consistent decisions concerning the mechanical condition of the circuit breaker.

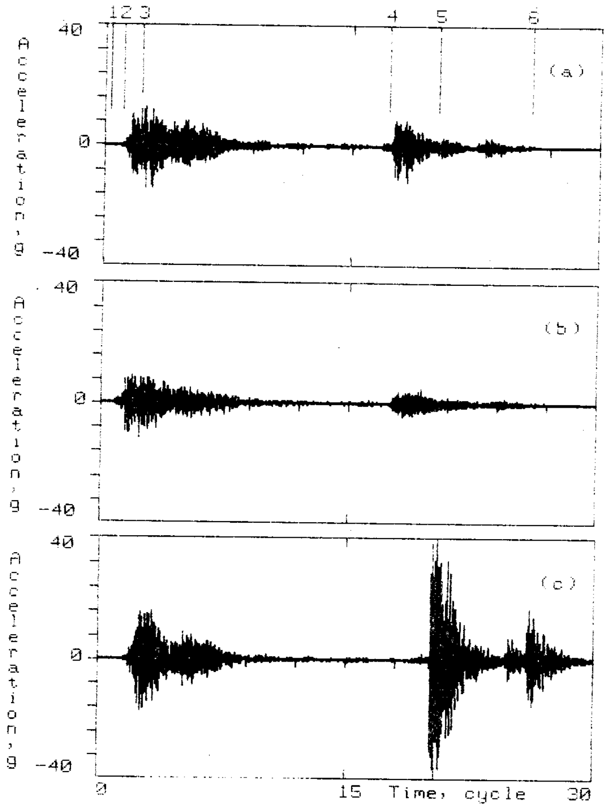

Fig. 3. Wall acceleration signals during trip operation. General Electric FHK-239 circuit breaker; 115 kV oil. (a) Normal; (b) Deactivated overtravel buffer spring; (c) Deactivated shock absorber. Events: 1. trip signal, 2. motion starts, 3. contacts separate, 4. shock absorber impacted, 5. shock absorber support impacted, 6. stop.

In Fig. 4, acceleration signals are presented for the McGraw-Edison circuit breaker. The data were obtained, on the side of the tank of pole 2, during close operations. The signals for the two abnormalities introduced--reduced contact penetration (Fig. 4b) and loose contacts (Fig. 4c)--appear very similar to those of the unit in normal condition (Fig. 4a). The imposed abnormalities, physically relatively subtle in nature, clearly then require signal processing for consistent (and correct) decision-making.

In Fig. 5 are shown two measurements recorded on the side of the tank of the BBC circuit breaker during a close operation. Figure 5a illustrates a normal operation. In Fig. 5b, eroded stationary contacts had replaced the new contacts of Fig. 5a--other adjustments remaining the same. The changes in the time trace due to contact erosion is not large, requiring signal processing for diagnosis; again, this abnormality is considered to be a subtle change (at least) from a vibration diagnostics point of view.

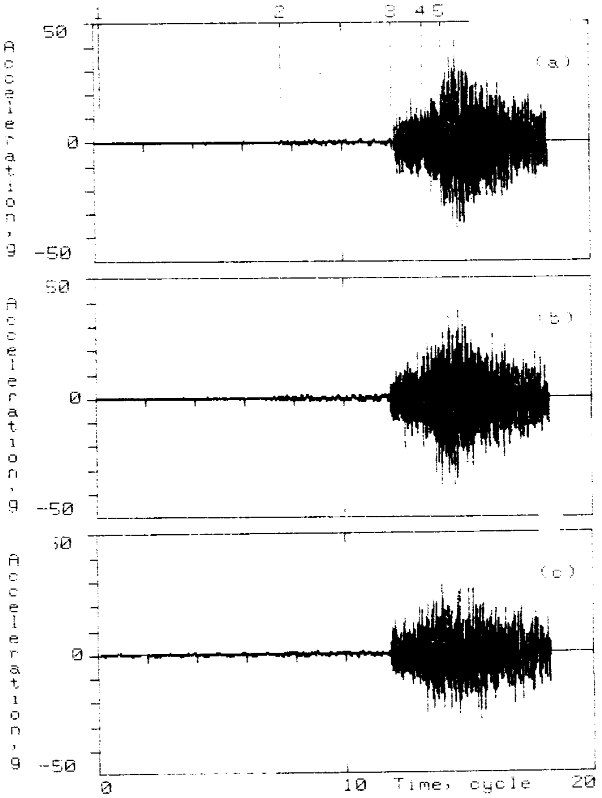

Fig. 4. Wall acceleration signals during close operation. McGraw-Edison RHF-90 circuit breaker; 242 kV oil. (a) Normal; (b) Reduced contact penetration; (c) Loose contacts. Events: 1. close signal, 2. motion starts, 3. isolating contacts touch, 4. main contacts touch resistor, 5. main contacts touch stationary contacts, and mechanism touches kick-off spring.

SIGNAL PROCESSING AND DECISION-MAKING

Introduction

Signal processing techniques, in conjunction with automatic decision-making procedures, provide a pattern recognition system that can automatically detect the defects of circuit breakers. As shown in Fig. 6, a pattern recognition system generally consists of two parts: a feature extractor and a classifier [2]. The feature extractor is a signal processor that presents the signal in a manner which enhances the differences between normal and abnormal behavior. The classifier is an automatic decision-maker.

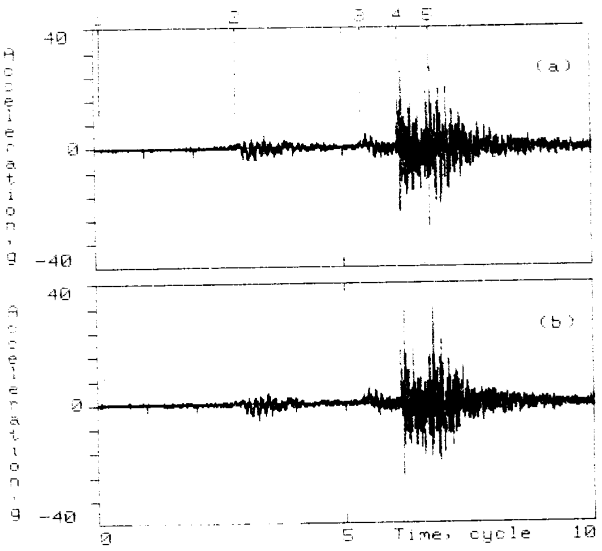

Fig. 5. Wall acceleration signals during close operation. BBC PA-40 circuit breaker; 242 kV SF$_6$. (a) Normal; (b) Eroded contacts. Events: 1. close signal, 2. motion starts, 3. contacts touch, 4. bumber impacted, 5. stop.

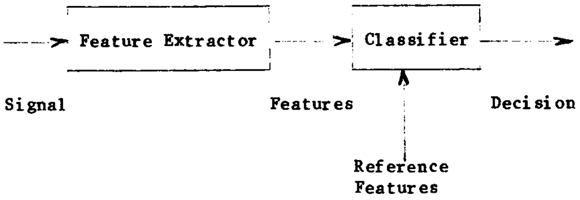

Fig. 6. A pattern recognition system.

Signal processing techniques denoted by the terms modified spectral (MS) analysis and structural modification (SM) analysis are employed as feature extractors. The modified spectral analysis yields a set of spectra of any signal. This technique is effective in extracting useful information about the signal and is simple to implement in the frequency domain (in which power spectra are obtained). Structural modification analysis is a more sophisticated signal processing method that requires vibration signals from both the exterior and the interior of a circuit breaker. In this method, the effects of the intervening structure and interrupting medium are incorporated so as to enable the determination of the signal that is characteristic of the interior source.

As can be seen from the previously discussed data, decision-making by a human being, via point-by-point observation of pairs of signals (the normal signal and the [unknown] test signal), is costly and may be inconsistent--particularly when differences between signatures are relatively small. Through the classification technique developed (the inputs to the classifiers being the earlier noted feature extractors), signatures at a given condition are characterized quantitatively (i.e., numerically) according to their mean value and standard deviation. Critical (or threshold) mean values of the test signals, in respect to the mean values associated with the normal signatures and the standard deviations of the normal and test signatures, are established in relation to a desired, predetermined confidence level. [In the present program, the confidence level was 97.5 percent, i.e., the probability of a circuit breaker being declared abnormal when it is normal is 2.5 percent; under these conditions, and for typical abnormalities tested, the probability of the unit being declared normal when it is abnormal is less than 1 percent.]

The several feature extractors employed address different aspects of the spectra obtained. Consequently, for a given operating condition, should any feature extractor and its associated classifier indicate the threshold (or critical) value to have been exceeded, the circuit breaker is then declared to be in abnormal condition. Thus, the combination of feature extractor and classifier is used to determine whether a circuit breaker is in normal or abnormal condition.

In operation, at least three MS analyzers were used as feature extractors; SM analyzers were implemented whenever the data were available. Each feature extractor was connected to a classifier. Each classifier stored the proper normal features; the input feature (of unknown classification, in principle) was characterized numerically in respect to the threshold value. In this arrangement, the classifications (i.e., normal/abnormal) determined by these classifiers might not all coincide with each other. As noted above, the circuit breaker was declared to be in an abnormal condition if at least one of the classifiers so indicated, i.e., if the decision ratio, DRn [DRn = QAn/THn; where QAn = mean value characterizing abnormality n and THn = threshold (or critical) mean value for abnormality n] > 1.00.

It should be noted that in the field (i.e., sites at the electric utilities), the mechanical condition of a test circuit breaker would generally be unknown. In the present paper, the mechanical condition of the various test units at the manufacturers and at the University at Buffalo was known (either normal or with an abnormality introduced)--so as to develop and to demonstrate the methodology.

Details of the signal processing and decision-making techniques will be presented in a following paper.

As shall be seen, MS analysis of external vibration signals, followed by classifiers, can detect abnormalities of circuit breakers in many, but not all, cases. The employment of SM analysis enables the detection of subtle changes, which may not be discerned through MS analysis of the external signals. The combination of SM and MS analyses has, to date, led to correct decision-making in all cases tested.

RESULTS AND DISCUSSION

In this section, applications of the signal processing and decision-making techniques, described in the previous section, will be illustrated for the four circuit breakers noted earlier: Siemens (BZO-121; 115 kV oil), General Electric (FHK-239; 115 kV oil), McGraw-Edison (RHF-90; 242 kV oil), and BBC (PA-40; 242 kV SF_6). The results will point to the value of using several (at least three) MS analysis classifiers, together with the SM analysis classifiers.

In the tables associated with the cases studied, the following notation applies: QN is the mean value characterizing the unit in normal condition; QAn is the mean value characterizing the unit having abnormality n; THn is the threshold (or critical) value for a unit having abnormality n; DRn is the decision ratio (QAn/THn). [For a given circuit breaker test, as stated earlier, when the value of DRn exceeds unity for any classifier, the unit is declared to be in an abnormal condition.] Further, use of the same MS and SM numbers (e.g., MS 5 and SM 5) indicates that the same aspects of the spectrum are treated by the two analyses.

The results obtained are based upon signal processing and decision-making methods associated with acceleration signals similar to those shown in Figs. 2-5.

Case 1. Siemens [BZO-121; 115 kV Oil]

Table 1 illustrates the results of the signal processing and decision-making techniques employed for the normal and imposed abnormal operating conditions of the Siemens circuit breaker. For this case, three sets of modified spectral analysis (MS1, MS2, and MS3) were carried out to decision-making [structural modification data were not available]. All MS analyses clearly and correctly indicated the presence of the respective abnormalities. In the case of the most obviously discernable abnormality (the combination of eroded contacts, misaligned contacts, and deactivated

Table 1
Siemens Circuit Breaker [BZO-121; 115 kV Oil]
[Top of Tank; Trip Operations]

Condition	MS 1	MS 2	MS 3	SM
QN	9,250	9,296	7,098	NA
TH1	12,928	13,878	11.108	NA
Q A1	47,498	44,119	28,129	NA
DR1	3.67	3.18	2.53	NA
TH2	12,190	13,377	10,891	NA
Q A2	71,336	33,479	27,784	NA
DR2	5.85	2.50	2.55	NA
TH3	12,435	13,138	10,888	NA
Q A3	101,079	51,229	50,548	NA
DR3	8.13	3.90	4.64	NA

NOTE: NA = data not available
DRn = decision ratio n = QAn/THn
Q A1 = mean value characterizing abnormality 1 - shortened toggle adjustment
Q A2 = mean value characterizing abnormality 2 - overcompressed tailspring
Q A3 = mean value characterizing abnor- of eroded contacts, misaligned contacts, and deactivated shock absorber
QN = mean value characterizing the normal condition

shock absorber - Fig. 2d), the largest decision ratios, QAn/THn, were obtained--ranging from 3.90 to 8.13. The least discernable abnormality (shortened toggle adjustment - Fig. 2b) yielded decision ratios in the range from 2.53 to 3.67. Decision ratios for the overcompressed tailspring (Fig. 2c) were in the range from 2.55 to 5.85.

Case 2. General Electric [FHK-239; 115 kV Oil]

This case illustrates the capability of the methodology to distinguish subtle as well as readily discernible changes. With the buffer spring deactivated, the acceleration signals (Fig. 3b) are seen to be very similar to those of the normal configuration (Fig. 3a). In Table 2, the decision ratios obtained for two (MS 4 and MS 5) of the three modified spectral analyses are greater than unity (having values of 1.15 and 1.35, respectively), thereby, according to the criteria established, indicating the unit to be in abnormal condition. The decision ratio for MS 6 is less than unity. Note that the structural modification analysis (SM 5) also indicates the unit to be in abnormal condition. A larger value of the decision ratio for SM 5, 2.80, in respect to that of MS 5, 1.35, is found. The corresponding greater sensitivity of the SM analysis is derived through a reasonable accounting of the effects of the structure and interrupting medium intervening between the internal source and the externally measured signal.

When the shock absorber is deactivated, the acceleration signals obtained (Fig. 3c) clearly become substantially different from the normal data of Fig. 3a. Correspondingly, all decision ratios are well in excess of unity. The modified spectral analyses--MS 4, MS 5, and MS 6--have values of 16.50, 1.42, and 19.89, respectively; that of the structural modification analysis, SM 5 is 44.71. The SM analysis again exhibits greater sensitivity than the MS analysis -- i.e., SM 5 (44.71) and MS 5 (1.42).

Table 2
General Electric Circuit Breaker
[FHK-239; 115 kV Oil]
[Top of Tank; Trip Operation]

Condition	MS 4	MS 5	SM 5	MS 6
QN	506	375	5,482	128
TH1	634	437	11,445	191
QA1	728	591	32,099	124
DR1	1.15	1.35	2.80	0.65
TH2	627	438	230	1,190
QA2	10,344	623	10,284	23,644
DR2	16.50	1.42	44.71	19.89

NOTE: DRn = decision ratio n = QAn/THn
QA1 = mean value characterizing abnormality 1 - deactivated buffer spring
QA2 = mean value characterizing abnormality 2 - deactivated shock absorber
QN = mean value characterizing the normal condition

Case 3. McGraw-Edison [RHF-90; 242 kV Oil]

The two abnormalities imposed on the McGraw-Edison circuit breaker--reduced contact penetration and loose contacts--yielded acceleration signals (Figs. 4b and 4c, respectively) that differed very slightly from that of the normal unit (Fig. 4a), thus indicating physical changes of a subtle nature. The corresponding feature extractors--three modified spectral analyses (MS 7, MS 8, and MS 9) and three structural modification analyses (SM 7, SM 8, and SM 9)of Table 3--although successful in detecting the abnormalities, experienced difficulties on an individual basis. For the case of reduced contact penetration, only two of the six decision ratios [MS 8 (1.08) and SM 8 (1.69)] indicated the unit to be in abnormal condition. With loose contacts introduced, five of the six decision ratios correctly indicated the presence of an abnormality [MS 7 (1.07), MS 8 (1.13) and SM 8 (1.92), MS 9 (1.13) and SM 9 (1.33)]. Note again the generally higher values of the SM analyses in respect to those of their MS counterparts.

Table 3
McGraw-Edison Circuit Breaker [RHF-90; 242 kV Oil]
[Side of Tank; Close Operation]

Condition	MS 7	SM 7	MS 8	SM 8	MS 9	SM 9
QN	5,027	2,802	874	4,511	4,343	2,624
TH1	5,771	3,361	987	6,654	4,654	2,885
QA1	4,651	2,571	1,066	11,244	4,094	2,652
DR1	0.81	0.76	1.08	1.69	0.88	0.92
TH2	5,623	3,361	967	9,978	4,678	4,328
QA2	6,020	1,900	1,092	19,151	5,292	5,748
DR2	1.07	0.57	1.13	1.92	1.13	1.33

NOTE: DRn = decision ratio n = QAn/THn
QA1 = mean value characterizing abnormality 1 - reduced contact penetration
QA2 = mean value characterizing abnormality 2 - loose contacts
QN = mean value characterizing the normal condition

Case 4. BBC [PA-40; 242 kV SF_6]

Here, the imposed abnormality on the BBC circuit breaker, eroded stationary contacts, again yielded acceleration signals (Fig. 5b) that appeared very similar to those of the puffer unit in normal condition (Fig. 5a)--indicating, once more, the introduction of a subtle physical change. The three modified spectral analyses of Table 4 (MS 10, MS 11, and MS 12) and the structural modification analysis (SM 10) all correctly detected the presence of the abnormality. The decision ratios were generally significantly greater than unity [MS 10 (1.64) and SM 10 (1.77), MS 11 (1.36), and MS 12 (1.62)].

Table 4
BBC Circuit Breaker [PA-40; 242 kV SF_6]
[Side of Tank; Close Operation]

Condition	MS 10	SM 10	MS 11	MS 12
QN	615	19	49	516
TH1	952	52	90	893
QA1	1,565	92	122	1,444
DR1	1.64	1.77	1.36	1.62

NOTE: DRn = decision ratio n = QAn/THn
QA1 = mean value characterizing abnormality 1 - eroded contacts
QN = mean value characterizing the normal condition

SUMMARY AND CONCLUSIONS

Through the use of noninvasive diagnostics, the assessment of the mechanical condition of a circuit breaker, i.e., whether the unit is in normal or abnormal condition, has been successfully determined. Tests were conducted upon oil (principally) and SF_6 circuit breakers at three manufacturers and at the University at Buffalo.

Test procedures have involved obtaining vibration signals from transducers placed along the external surfaces of (and, under certain conditions, within the interior of) a circuit breaker. By applying data processing (modified spectral analysis and structural modification analysis) and decision-making techniques, the mechanical condition of a unit under any given operating condition (normal and with various imposed abnormalities) was determined quantitatively (i.e., numerically). Based upon the criterion that a decision ratio [the ratio of the mean value characterizing the circuit breaker under test (usually with an abnormality introduced) to that of a calculable threshold (or critical) value] greater than unity indicated the unit under consideration to be in abnormal condition, the diagnostic procedures successfully identified the presence of all abnormalities imposed.

ACKNOWLEDGEMENTS

The research was supported by the Electric Power Research Institute, Research Project 2747-1, and by the New York State Energy Research and Development Authority, Agreement No. 1859-EEED-TC-86.

The authors acknowledge the support and encouragement of Mr. Glenn Bates of the Electric Power Research Institute and Dr. Fred V. Strnisa of the New York State Energy Research and Development Authority. The contributions of Mr. George P. Adams, Mr. Howard J. Lieberman, and Mr. Raymond C. Seebald of Niagara Mohawk Power Corpo-ration; Mr. John W. Charlton of New York State Electric and Gas Corporation; and Mr. Richard Cohen, Mr. Richard B. Kruger, and Mr. Shalom Zelingher of New York Power Authority are acknowledged.

The support and cooperation of Mr. David S. Johnson and BBC Brown Boveri, Inc. (Greensburg, PA); Mr. Gordon A. Wilson and McGraw-Edison Power Systems, Cooper Industries (Canonsburg, PA); and Mr. William E. Harper and Siemens Energy and Automation, Inc. (Jackson, MS) are acknowledged.

The assistance of Mr. Daniel J. Walch and Ms. Tina M. Rottmann of the State University of New York at Buffalo in the setup and carrying out of experiments is acknowledged.

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