Vibration Analysis for Diagnostic Testing of Circuit-Breakers

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Abstract--**In order to assess the feasibility of vibration analysis for diagnostic testing of high-voltage circuit-breakers a comprehensive field test program has been carried out. Vibration patterns from 31 breakers (93 identical single-phase units) have been acquired, compared and analyzed. The breakers were assumed to be in good condition with no known irregularities at the time of testing. However, several serious faults, including an incipient rupture of the contact plug shaft, an incorrectly assembled crank, and major lubrication problems were disclosed. Thus, this "blind test" performed under realistic conditions on circuit-breakers in normal service demonstrates that vibration analysis can be a reliable and suitable tool for non-invasive diagnostic testing.**

I. INTRODUCTION

Electric utilities show an increasing interest in reducing maintenance costs without sacrificing reliability and safety. This applies to all components of high-voltage transmission and distribution systems, including the circuit-breakers. Presently, there is a clear tendency among many utilities to shift from periodic to condition-based maintenance. Instead of doing revisions and overhauls at fixed time intervals, e.g. once every 10 or 15 years, many utilities attempt to carry out these time consuming and costly operations only when required.

A crucial element in such a condition-based maintenance practice is the ability to assess the need for invasive inspections and overhauls. Consequently, recent years have brought an increasing focus on and interest in various techniques for diagnostic testing and monitoring, and several new methods have been proposed [1].

One of these novel approaches is to apply vibration analysis for diagnostic testing of circuit-breakers. The mechanical vibrations from closing and opening operations are recorded by using accelerometers and a data acquisition system. These vibration "signatures" or "fingerprints" are compared with a reference, which can be an earlier recording from the same breaker or the signature from another of the same type. The basic idea is that mechanical malfunctions, excessive contact wear, misadjustments and other irregularities and faults can be detected as changes in the recorded vibration patters.

Several research groups have carried out work according to this concept, but different approaches for analyzing and comparing the vibration patterns have been pursued. Routines involving Fourier analysis and event detection algorithms [2], [3], dynamical time warping [4], [5], and artificial intelligence [6] have all been claimed successful in detecting faults.

However, the testing has so far primarily been performed on one or a few circuit-breakers installed in a laboratory environment with the faults introduced deliberately. Thus, the condition of the circuit-breakers has been known, so the person who carried out the diagnostic test has been knowing what to look for.

The investigation reported on in this paper is different in these respects. It was carried out on a large number of circuit-breakers in normal service, and secondly, the breakers were assumed to be in good condition with no known irregularities at the time of testing. Thus, this is a true "blind test" carried out under realistic circumstances, with the objective of exploring the feasibility of vibration analysis as a method for diagnostic testing of circuit-breakers.

This paper starts with a brief description of the applied method and procedures. The main sections present the results from diagnostic testing of 31 circuit-breakers (93 equal, single-phase units). A discussion of advantages and drawbacks of vibration analysis compared to conventional diagnostic methods completes the report.

II. TEST PROCEDURE

A. Acquisition of Vibration Patterns

Vibration analysis is a non-invasive method. Three or four accelerometers are mounted externally on each single-phase unit; usually one on each arcing chamber (provided that the circuit-breaker is disconnected and grounded, or of the dead tank type),

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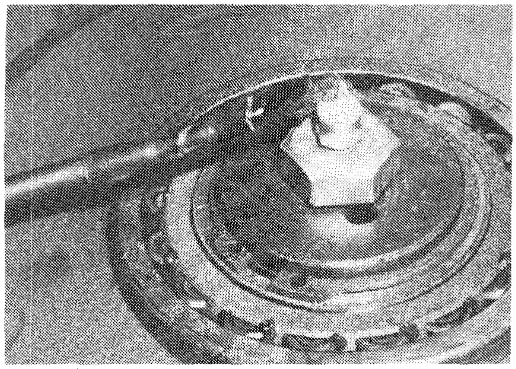


Fig. 1. Accelerometer mounted on part of a circuit-breaker.

one in the operating mechanism and one somewhere between. Fig. 1 shows a 2 gram accelerometer mounted on a screw which in turn is screwed into an existing hole in a rotating shaft of a circuit-breaker operating mechanism.

The vibration signatures from each of the sensors are recorded during closing and opening operations by using a standard 14 or 16 bit PC-based data acquisition system or a transient recorder.

The recorded signals consist of a sequence of vibration "events", each corresponding to a mechanical event taking place in the breaker. Recordings from corresponding sensor locations on different units are usually fairly similar, as shown in Fig. 2.

For free-standing live tank circuit-breakers the dominant frequency components of the obtained signals are usually below 20 kHz, but in some events frequencies up to 30 - 40 kHz are observed. The signal-to-noise ratio is normally excellent, typically around 70 dB.

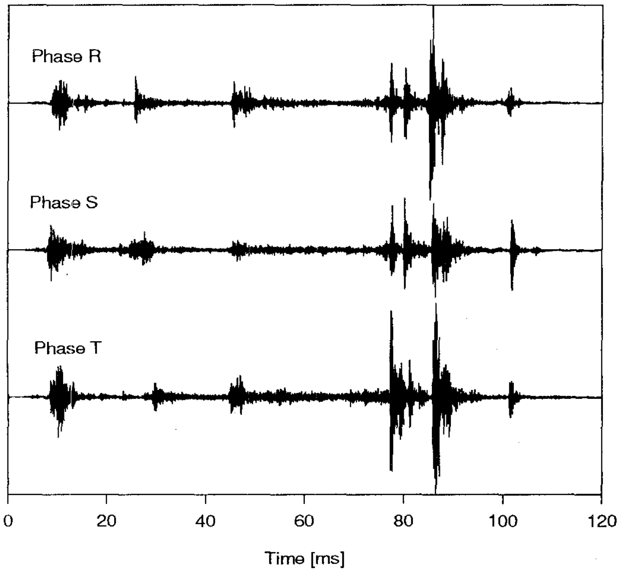


Fig. 2. Vibration signatures obtained in the driving mechanisms of the three phases during closing of a spring-operated 300 kV SF_6 puffer breaker.

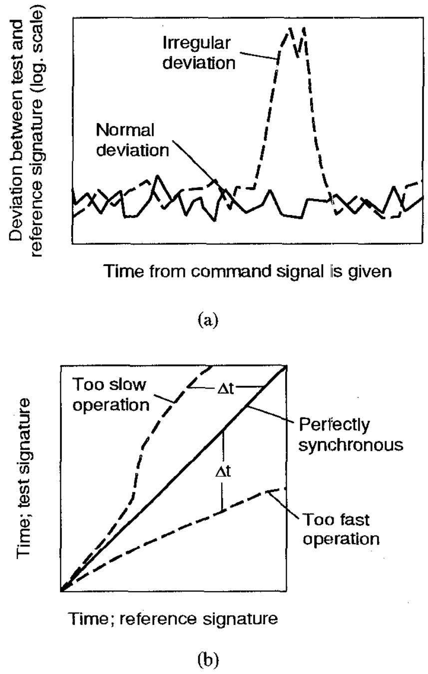
Further details on the data acquisition system as well as several examples of vibration patterns have been published earlier [4], [7].

B. Interpretation and Comparison

Acquiring vibration patterns is normally straightforward, whereas developing reliable algorithms for detecting deviations between such patterns is far more difficult.

In this work Fourier analysis and dynamical time warping (DTW) have been applied. In short, events in one signature are compared with the events of the reference signature by considering the vibration amplitudes, their frequency content and the time at which the events occur. The algorithm is highly sensitiv for deviations also in the rather quiet periods of a signature, as well as for relatively small shifts in frequency content. Thus, the analysis may reveal discrepancies that are not obvious from a quick look at the recorded vibration patterns, for example when being displayed as in Fig. 2. More detailed descriptions of the algoritms are given in a previous paper [4].

The output of the analysis is two graphs, see Fig. 3. The *Deviation vs. time* diagram, Fig. 3 (a), shows discrepancies in frequency content and amplitude between the two vibration signatures. The deviation is given at a logarithmic scale [4]. The *Time vs. time* diagram, Fig. 3 (b), displays how synchronous the events in the two signatures come. For example, if a certain event occurs after 25 ms in one signature and after 28 ms in the other, the point (x=25, y=28) appears as a part of the path in Fig. 3 (b).



(a)

(b)

Fig. 3. The output of the computerized comparison between vibration patterns (schematically): *Deviation vs. time* (a) and *Time vs. time* (b) diagrams. (See text.)

The point zero on the time axes is when the electric command signal is given.

The solid curves in Fig. 3 represent a "normal" result, i.e. the output from a comparison between two vibration patterns that are essentially equal, both with respect to frequency content and timing.

The broken lines, on the other hand, illustrate schematically how various deviations come out. An additional, changed or missing event in one of the signatures yields a high deviation value in Fig. 3 (a) at that point of the breaker operation, while irregularities that affect the speed of the breaker operation (e.g. poor lubrication, overcompressed spring, etc.) lead to a path in Fig. 3 (b) off the straight diagonal.

Even though two circuit-breakers appear identical, some deviations in their vibration patterns are always observed, and furthermore, no vibration pattern recording is completely reproducible. Hence the crucial part of the analysis is to be able to distinguish signature deviations caused by irregularities in the circuit-breaker from the normal, statistical scatter seen among units in good condition.

Note that an irregularity not necessarily affects both the diagrams presented in Fig. 3. A circuit-breaker can have a serious fault and still operate with the same speed and timing. Conversely, lack of lubrication, for example, can lead to unacceptably slow breaker operation, but does rarely change the content of the vibration events, only their time of occurrence.

III. APPLICATION ON 31 CIRCUIT-BREAKERS IN NORMAL SERVICE

The test method has been applied on a population of 31 spring-operated SF_6 puffer breakers of the same type, at four different outdoor substations. Each breaker consists of three equal, separate single-phase units, so the investigation comprises totally 93 identical units. The circuit-breakers are rated for 145 kV, have one arcing chamber and were installed in the period 1978 - 82. Since then each of them has performed between 50 and 500 close-open operation cycles. There was no particular reason for choosing this circuit-breaker model for the investigation.

The manufacturer specifies a full revision after 10 years of service, and 13 of the circuit-breakers were in 1989 subjected to major overhauls. All 13 had their operating mechanism completely disassembled, and for nine of them the revision also included opening and inspection of the arcing chambers and the contacts. Only minor irregularities were disclosed. In particular, the arcing chambers and the contacts were virtually like new.

For the remaining 18 circuit-breakers maintenance has been restricted to visual inspections and minor non-invasive work, primarily cleaning and lubrication, carried out by the substation personnel.

The vibration patterns, from both closing and opening operations, at three well-defined locations on each of the 93 units were recorded in 1992. The data acquisition took 1 - 2 hrs per circuit-breaker, of which most of the time was spent on moving a lift around.

The subsequent vibration analysis was carried out by comparing corresponding measurements from neighboring units. That is, the closing signature obtained on the arcing chamber of phase R was compared to that of phase S, and so on.

IV. RESULTS

A. Overview

The large number of circuit-breakers included in the survey provides a good statistical basis for distinguishing irregular signature deviations from the regular or natural ones. Considering the *Deviation vs. time* plots, the borderline between the maximum statistical scattering and irregular discrepancies was, by experience, found to lie around 12 units. With regard to timing, the manufacturer specifies a maximum permissible deviation in closing times between the phases of a circuit-breaker of 5 ms. Thus if *Time vs. time* plots show deviations exceeding this value, the measurements were subjected to more careful examinations.

The main conclusions from the analyses can be summarized as follows:

- In 8 of the 93 breaker units clear indications of poor lubrication were found, and re-lubrication was recommended.

- In 3 units the vibrations obtained on the arcing chamber deviated so much from the rest of the population that it was recommended to open for inspection.

These recommendations were given, in written reports, to the utilities that owned the circuit-beakers. Less than half a year later and before the utilities had done anything, there were two cases of severe malfunction on the investigated circuit-breakers. Both were attributed to lubrication problems. The utilities then decided to follow the recommendations. Cleaning and relubrication of the operating mechanisms of a large number of breakers were initiated. Moreover, the three units with deviating arcing chamber signatures were opened for inspection, and two of them turned out to contain serious faults.

The following sections present more details from this survey, including *Deviation vs. time* and *Time vs. time* plots, findings from inspections, and also results from new measurements carried out after repair or relubrication.

B. Lubrication Problems

1) Diagnoses: Fig. 4 shows the output diagrams from an intercomparison between closing operations of phase S and T of one of the 31 investigated circuit-breakers. The *Deviation vs. time* plot shows that the difference between the vibration signatures is well below 12 units throughout the operation, indicating no notable differences with regard to frequency content and amplitude of the vibration events of these two recordings.

The *Time vs. time* diagram on the other hand shows a clear deviation in timing between the two phases. During the first 20 ms they are synchronous, but from then on phase T gradually

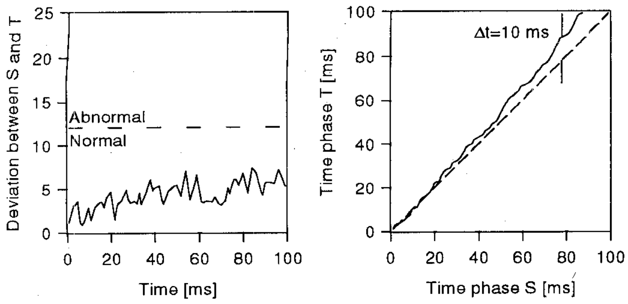


Fig. 4. Comparison between two breaker units of which one (phase T) shows a delay which is assumed to originate in poor lubrication in the driving and transfer mechanism.

lags behind. Towards the end of the closing operation the difference is around 10 ms.

In Fig. 5 diagrams from another circuit-breaker are presented. Also in this case the deviation in frequency content and amplitude is insignificant, whereas the *Time vs. time* plot shows that the operation of phase T is severely delayed ($\Delta t \approx 15$ ms). However, here the deviation in timing occurs within the first 20 ms. For the rest of the closing operation the calculated "path" is parallel to the straight diagonal, indicating no further delays.

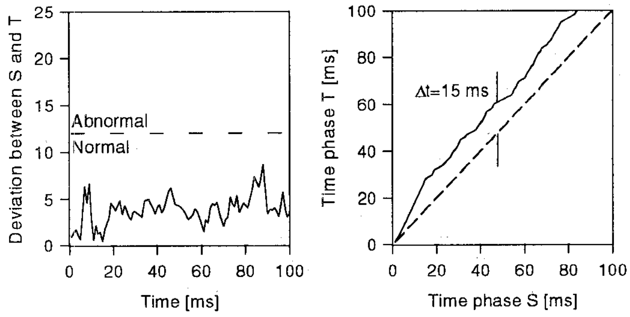


Fig. 5. Comparison between two breaker units of which one (phase T) shows a delay which is assumed to originate in poor lubrication in the release mechanism.

Among the investigated circuit-breakers four cases similar to that of Fig. 4 and three similar to the one shown in Fig. 5 were found. In addition, one circuit-breaker unit had both types superimposed, i.e., a significant delay within the first 20 ms as well as a gradually increasing time-lag during the rest of the operation.

The explanation and origin of these different "delay modes" were proposed by taking into account that in this type of circuit-breaker the contact plug starts moving around 20 ms after the command signal has been given. Deviations in timing that gradually develop from this point, as seen in Fig. 4 (b), signify that the speed of the contact movement is somewhat reduced. The most likely explanation is insufficient lubrication in the mechanical parts responsible for creating and transferring driving force to the moving contact.

Delays of the type shown in Fig. 5 were also assumed to be caused by poorly working lubrication. However, in these cases the delay occurs before the contact movement has started. The only parts active at this time are the relays, shafts, handles etc. that release the main spring, and consequently, the lubrication problems were assumed to be related to the release mechanism.

Thus in all these cases the timing differences were assumed to originate in poorly working lubrication. This conclusion is supported by the fact that none of the eight units showed significant discrepancies in the corresponding *Deviation vs. time* plots.

Consequently, based on the vibration analyses the owners of the circuit-breakers were recommended to relubricate five driving/transfer mechanisms and four release mechanisms, out of the 93 investigated.

2) Malfunctions: In February and June 1993 two of the four breaker units that earlier had got the diagnosis "poor lubrication in release mechanism" failed to operate. One did not open on command, the other did not close before until 15 s after the command signal was given. Close inspections carried out by the utility and by a serviceman from the manufacturer determined the malfunction to be caused by poorly working lubrication in parts of the release mechanisms.

These findings, together with the fact that seven out of the eight units alleged with lubrication problems were among the 13 circuit-breakers that had been overhauled, prompted the utility to do further investigations. It turned out, eventually, that the lubrication applied in the operating mechanism during these overhauls was only intended for use in SF_6 ambient and not in air. Consequently, a large number of circuit-breakers had to have their operating mechanism cleaned and relubricated with the correct type of grease.

3) New Measurements: In order to check whether the relubrication really had restored the condition of the circuit-breakers, new vibration signatures were recorded in November 1993. Fig. 6 shows diagrams from a comparison between signatures obtained before and after relubrication on the unit that got the diagnosis "poor lubrication in release mechanism" and later failed to close on command. Thus, this is a comparison between recordings on the same unit, not between two similar single-phase units as in Figs. 4 and 5.

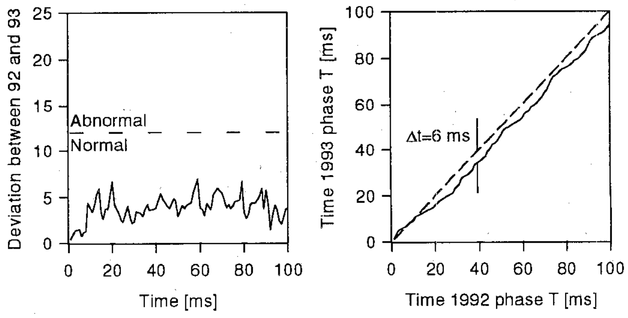


Fig. 6. Comparison between vibration patterns obtained before and after lubrication, indicating that the release mechanism now operates more swiftly.

The *Time vs. time* diagram shows that the release mechanism operates around 6 ms faster in 1993, indicating that the cleaning and relubrication have had a profound effect. The contact travel (i.e., from around 20 ms on) is unaffected, as expected.

C. Incorrectly Assembled Crank

1) Diagnosis: Another set of diagrams from the vibration analysis on 31 circuit-breakers is shown in Fig. 7. These diagrams came out by comparing signatures obtained at the operating mechanisms of two phases of a circuit-breaker during closing. Deviations significantly greater than the normal scatter are seen both with regard to amplitude/frequency content (left plot), and timing (right plot).

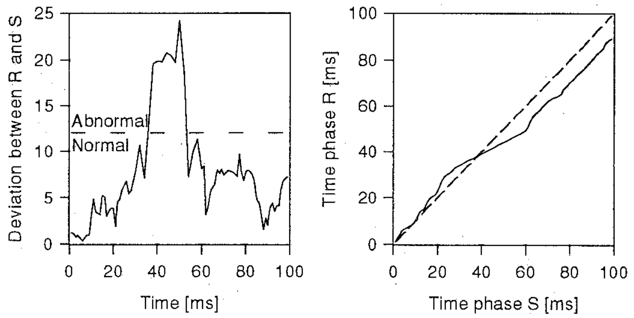


Fig. 7. Diagrams indicating major discrepancies between phase R and S of a circuit-breaker.

Comparisons between phase R and T, and also between S and T revealed that the deviations observed in Fig. 7 stem from the phase R unit. Both phase S and T show normal vibration patterns.

Fig. 8 shows the vibration traces that, when compared, produce the diagrams of Fig. 7.

These underlying data are consistent with the *Deviation vs. time* and *Time vs. time* plots. The contact movement of phase R starts a few milliseconds later than in phase S, but is completed as much as 10 ms earlier. (The powerful events starting at around 23 ms / 19 ms and at around 75 ms / 87 ms show when the contact travel starts and stops, respectively.) Furthermore, the vibration events recorded between 30 and 70 ms are clearly different. (All details of the vibration patterns in this rather quiet period are, however, not visible in Fig. 8.)

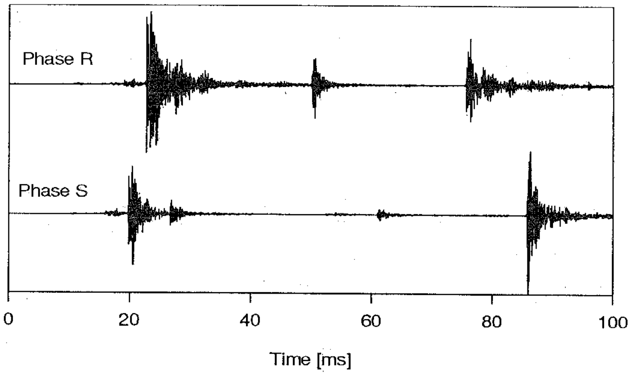
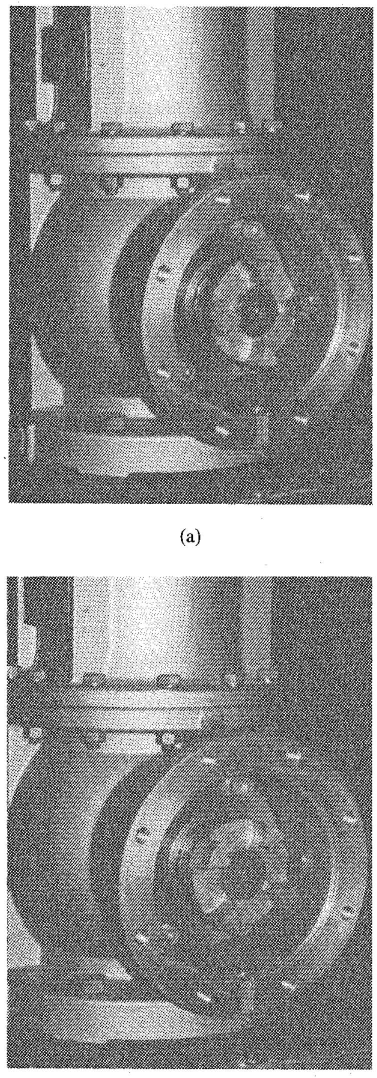


Fig. 8. Vibration patterns leading to the diagrams in Fig. 7.

Also when comparing the signatures from opening operations or from other sensor locations, significant deviations appear. The nature of all the irregularities indicated that the contact travel in some way was irregular, and it was recommended to dismantle the unit and open the arcing chamber for inspection.

2) Inspection: The reason for the deviating vibration patterns was that a four-toothed gear wheel that transfers the mechanical power from the driving mechanism to the moving contact was mounted 30 degrees out of position, see Fig. 9.



(a)

(b)

Fig. 9. Correctly (a) and incorrectly (b) assembly of the four-toothed gear on the crank shaft. The driving mechanism is to be attached to the flanges and a rotational movement is transferred to the crank with a similar four-toothed gear on the driving mechanism.

When correctly assembled the crank transforms a 180 degrees rotation of the shaft from the driving mechanism to a 20 cm vertical movement during a breaker operation. This brings the moving contact from its uppermost to its lowermost position, or vice versa. This maneuver was to a large extent altered in phase R. The moving contact did neither start nor stop in its vertical end-positions.

Close inspection of the design of the contacts revealed that the insulation distance in open position as a result of this was reduced by around 10 %. Probably more important is that the main contacts barely touched each other when the breaker was in closed position. The arcing contact is not designed to carry load currents continuously, so a severe overheating has probably been avoided with minute margins.

Furthermore, the incorrect assembly also affected the contact speed and the gas flow at the critical moments when the arc is extinguished. Hence, the current-breaking capability of this unit was probably significantly reduced.

This circuit-breaker was among those that underwent a complete revision in 1989, and it is believed that the fault was introduced at that time. Considering the fact that it is possible to assemble such a critical part as this four-toothed wheel incorrectly, it is however felt that the design in itself is to blame, as least partly.

3) New measurements: This circuit-breaker was not put back in service. Thus no new vibration signatures have been acquired.

D. Unusual Vibration Pattern from the Arcing Contacts

1) Diagnosis: Fig. 10 shows diagrams from a comparison between the signatures obtained on two of the arcing chambers of a circuit-breaker. The large deviation occurs at the stage of the opening operation when the arcing contact members are sliding along each other, just before they separate.

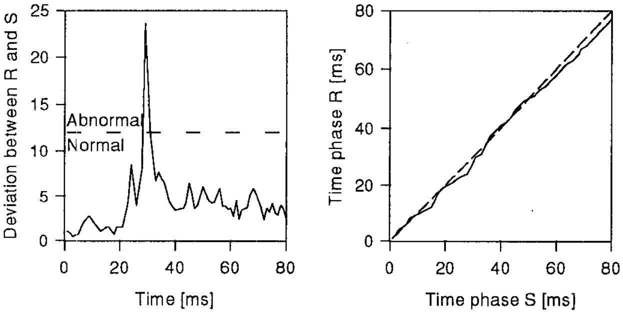


Fig. 10. Diagrams from opening operations of phase R and S of a circuit-breaker, indicating major differences in their vibration patterns.

A closer examination of the vibration patterns, see Fig. 11, and also comparisons with recordings from other breakers clarify the character of the deviation. The event in the phase S signature starting at around 23 ms is highly unusual in that it consists primarily of frequencies below a few kilohertz. In all the other 92 units investigated, the sliding of the arcing contact members caused vibrations in the 10 - 30 kHz range.

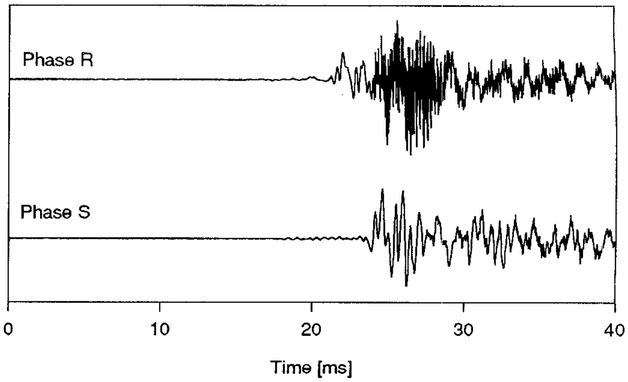


Fig. 11. The first 40 ms of the vibration patterns from which the diagrams in Fig. 10 are produced.

This deviation was assumed to be related to the sliding friction between the arcing contact members. Thus, it was suggested that the arcing contact members in phase S were of a somewhat different material or dimensions than in the rest of the population. This circuit-breaker was completely dismantled during the revision in 1979, and a possible explanation put forward was that the arcing contact members of phase S at that time had been replaced with new ones made of a slightly different material or simply from a different production batch. It turned out, however, that the arcing contacts were not mentioned at all in the revision report. Consequently, it was recommended to open the arcing chamber for inspection.

2) Inspection: For the sake of comparison the arcing chambers of both phase R and S were opened. No signs of irregularities were found. The only visible difference between these two units was that the upper arcing contact (the rod or finger) in phase S appeared significantly less worn than that of phase R. The sliding tracks were narrower, there were less soot, and it contained fewer arc erosion spots.

Assuming that the revision report is complete and correct, and that the arcing contact not was replaced, no explanation of the observed deviation has been found.

3) New Measurements: New sets of vibration signatures were recorded after the inspection. They were in all respects equal to those obtained earlier; the unusual frequency content described above was still there.

E. Incorrectly Adjusted Moving Contact

1) Diagnosis: The vibration pattern from the arcing chamber of one of the 93 circuit-breaker units contained a very powerful additional event towards the end of the closing operation. Fig. 12 displays how this came out in the vibration analysis, while Fig. 13 shows the related signatures.

Close examination of Figs. 12 and 13 also reveals some additional, but less evident discrepancies after around 30 ms. The calculated deviation is approximately 9 units, and the path in the *Time vs. time* diagram is brought off the diagonal. From about 45 to 60 ms the arcing chamber signatures contain no new,

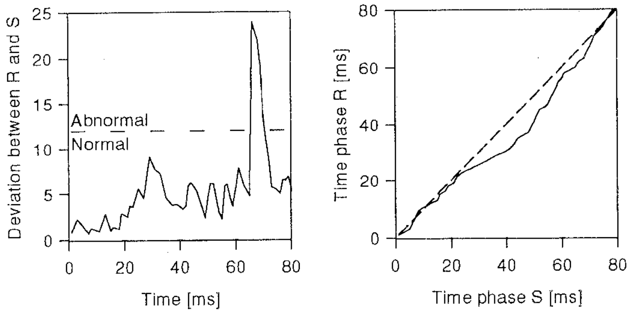


Fig. 12. Comparison between recordings of two units of which one (phase R) contains a powerful extra event. The input data are shown in Fig. 13.

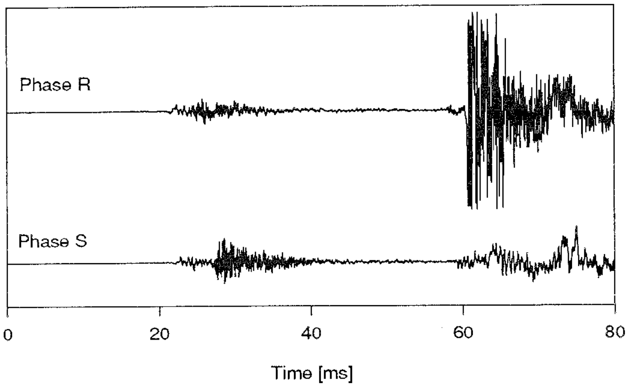


Fig. 13. Normal (phase S) and irregular (phase R) vibration signatures from the arcing chambers during opening operations.

distinct vibration events to "hook" the time-time analysis on. Moreover, the very strong extra event at 60 ms probably confuses the DTW algorithm, so in this case parts of the *Time vs. time* diagram may be somewhat incorrect.

Based on analyses of the vibrations shown in Fig. 13 and also of patterns obtained from the other sensors, it was suggested that the moving contact towards the end of an opening operation hit something it was not supposed to hit, or that some parts of it had loosened. It was recommended to dismantle the breaker for inspection.

2) Inspection: The reason for the irregular vibration signature was that the contact plug was adjusted 6 - 7 mm too low. Due to this, the main contact members did not penetrate as intended in the closed position, and the contact plug went too far down in open position. The latter caused it to hit a guiding ring close to the fixed puffer piston. The hit was very powerful, causing major indents, see Fig. 14, as well as the additional event in the vibration signature in Fig. 13.

Furthermore, the epoxy shaft on which the moving contact is mounted, was also damaged. As shown in Fig. 15, the epoxy was cracking underneath the metallic parts at the end of the shaft.

In 1987 an instrument transformer nearby exploded and damaged this circuit-breaker. It is believed that the misadjustment stems from the major repair that followed this incident.

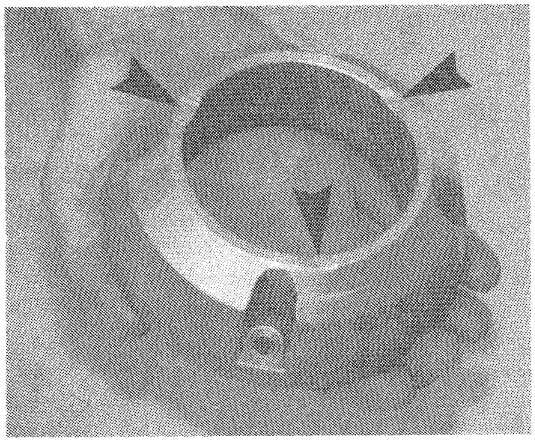


Fig. 14. Guiding ring with indents from the incorrectly adjusted moving contact.

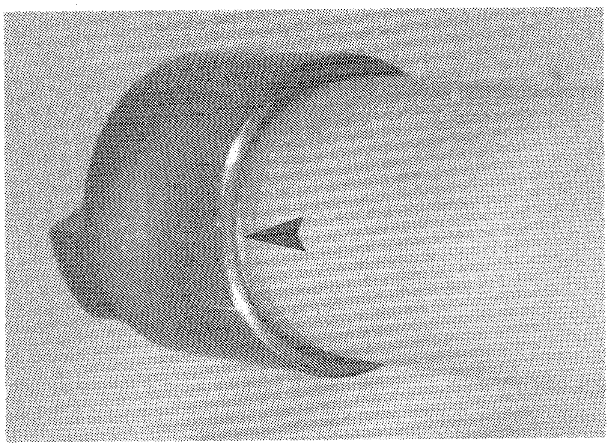


Fig. 15. End of the contact plug epoxy shaft with cracks around its circumference.

3) New Measurements: New vibration patterns were recorded after the parts shown in Figs. 14 and 15 had been replaced and the moving contact had been adjusted correctly. As shown in Fig. 16, the repair affected the vibration patterns to a large extent.

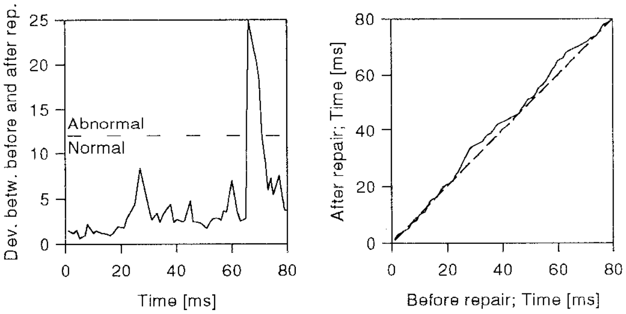


Fig. 16. Comparison between signatures obtained before and after repair, showing major changes.

V. DISCUSSION

Measurement of operating times (i.e. the time elapsed from application of command signal and till the contact closes or opens) is widely used as a diagnostic test on circuit-breakers. This is a simple method, but this work clearly illustrates its limitations; the operating times of the unit with an incorrectly adjusted moving contact were perfectly normal.

More advanced methods such as installing potentiometers or optical transducers in the circuit-breaker to register the contact travel during an operation yield far more information. For example, the incorrectly assembled crank leads to abnormal contact travel recordings and further investigations would probably have disclosed the fault.

Also the incorrectly adjusted moving contact is detectable by synchronous, combined operating time and contact travel measurements, as a low contact penetration. The most severe aspect of this misadjustment is that the impact caused the epoxy shaft to start cracking. This did not affect the contact travel near the make/break point, so the closing and opening velocities of the contact plug were probably well within the acceptable values. A careful examination of the damping and rebound characteristics of the motion trace may have indicated that the contact plug was hitting something. However, such analyses are not as common and well-established as contact stroke and velocity measurements.

A clear advantage of diagnostics based on contact travel and time measurements is that the determined parameters are easily apprehended. Contact velocity and position are less complicated conceptions than frequency content, amplitude and timing of vibration events. However, the *Time vs. time* diagrams determined from the vibration signatures contain essentially the same information as a time vs. position or contact travel trace. The former are less accurate and focus on deviations in timing between two recordings, rather than providing an absolute time vs. position relationship for one recording. The cases with lubrication problems reported on here demonstrate however, that such faults are readily detectable by the *Time vs. time* plots.

A major advantage with vibration analysis is that it has the potential of detecting faults and irregularities other than those affecting the contact travel and operating times. Furthermore, the equipment and computer programs are applicable on all types of circuit-breakers, including breakers in gas encapsulated substations. Contact travel measurements in contrast, require position transducers mounted on the circuit-breaker, and in some models moving parts cannot be accessed non-invasively.

Finally, it is worth noting that all faults and irregularities detected in this work are assumed to have been introduced during overhauls or repairs, carried out by the manufacturer service crew. Although this discouraging observation is not assumed to be representative, it serves as a strong incentive for doing non-invasive diagnostic tests instead of traditional overhauls.

VI. CONCLUSION

The feasibility of using vibration analysis for diagnostic testing of high-voltage circuit-breakers has been demonstrated though field testing, in which several serious faults were disclosed in the 93 identical circuit-breaker units investigated.

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