# ACOUSTIC DIAGNOSIS OF HIGH VOLTAGE CIRCUIT-BREAKERS

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Abstract - *A non-invasive technique for assessing the condition of circuit-breakers by considering the acoustic signals generated during non-energized switching is described. Mechanical malfunction, wear and other types of abnormal behaviour can be detected as changes in this acoustic "signature". Digital signal processing techniques known from speech recognition were successfully applied to extract, compare and present the information from the breaker signatures. A fault in the release mechanism which developed over time and eventually rendered one pole of a circuit-breaker inoperative, was detected in an early stage, demonstrating the efficiency of this diagnostic technique.*

*(Keywords: circuit-breakers, diagnostics, acoustic signatures, maintenance)*

## INTRODUCTION

Design and construction of high-voltage circuit-breakers are in several ways a mature technology. The majority of the circuit-breakers being installed today are of the $SF_6$ puffer type, and their reliability is very good.

$SF_6$ puffer breakers were introduced in the Norwegian power grid in the mid-seventies, and a considerable number were installed the following years. The manufacturers usually specify a periodic maintenance program, which in most cases includes a complete overhaul every 10 or 15 years. This work has been going on for a few years now, and some conclusions can be drawn with regard to the condition of these circuit-breakers and the need for maintenance.

In general, the breakers are found to be in excellent condition after more than ten years of service and up to 500 - 600 operations. Only minor irregularities that do not influence the circuit-breakers' operating ability have been disclosed. In particular, the arcing chamber and the contacts are virtually like new.

These overhauls, where the entire circuit-breaker is disassembled, are however, time-consuming and expensive. A general rule is that the costs are between one third and one half of the price of a new breaker, and the utilities are questioning the economic justification of such a comprehensive maintenance program on a 10 or 15 year old circuit-breaker. Moreover, it is well-known that the dismantling and reassembly itself may introduce faults.

On the other hand, there is not yet a good recommendation as to how long the contacts and other important parts of the circuit-breaker can be left uninspected. This is also a matter of discussion, in particular considering that these breakers are likely to be in service for decades to come. Earlier, the rapid increase in demand for electric power in many cases led to a replacement of 10 - 20 years old components, still in excellent condition.

Against this background, there has during the last few years been a growing interest in diagnostic methods for circuit-breakers. A number of techniques are in use, and new ones are under development [1]. Among the new approaches are to record the acoustic "signature" or "fingerprint" from a switching operation, and compare it with a reference signature [2], [3]. The reference can be an earlier recording from the same circuit-breaker or the signature from another of the same type. The basic idea is that contact wear, mechanical malfunction and other types of abnormal behaviour can be detected as changes in the acoustic signature of the breaker.

The present paper describes a diagnostic method based on these principles. All of the results reported here are from tests on a typical spring-operated $SF_6$ puffer breaker of the live tank type (BBC ELF 145 kV). This model has free-standing poles, each with its own driving mechanism. Preliminary measurements on other $SF_6$ puffer breakers did not reveal any notable differences in the acoustic properties. It is thus assumed that similar results can be found for other live tank $SF_6$ puffer breakers.

The report starts with a description of the instrumentation used for acquisition of the acoustic signatures from opening and closing of the circuit-breaker. Then follows a general overview of some features of these time-domain signals that are of importance in the present context. The routines used for processing and comparison of signatures are then described. Finally, the response of the developed diagnosis system to a breaker with defective release mechanism is shown and discussed.

## INSTRUMENTATION

The acoustic signatures from a switching operation are acquired by accelerometers mounted on the outside of the pole. The accelerometers used in the present work (B&K model 4344 and 4374) are only a few grams in weight, and are properly fixed to the

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circuit-breaker simply by using beeswax. The signatures are always recorded on circuit-breakers that are disconnected. Thus, the location of the accelerometers is not restricted to the grounded parts.

The signals from the acoustic sensors are amplified (Endevco 2721) and passed into a four channel, 16 bit resolution transient recorder (Analogic Data Precision 6000). Opening or closing is initiated by an electric pulse to a magnetic relay which in turn releases the main spring. This command signal also triggers the transient recorder. 8000 samples with an interval of 15 µs are recorded per channel, giving a record length of 120 ms. This sampling rate makes it possible to register frequencies up to 33 kHz, which is within the linear region of the frequency response of the accelerometers used.

Preliminary examination and plotting of the recorded time-domain signals are carried out by using the transient recorder. The data are then stored on a floppy diskette for further processing on a personal computer.

## ACOUSTIC SIGNATURES

Generation and propagation of sound in a circuit-breaker are very complicated processes. Many sources exist, and there is a large number of boundaries and interfaces that scatter, attenuate and in other ways greatly affect the propagation of the acoustic waves. Consequently, it is an extremely labourious task to obtain a detailed description of the acoustics of a circuit-breaker operation in mathematical terms. For example, the displacement of the contacts that occurs during opening or closing alters the acoustic properties significantly, making it necessary to apply time-dependent transfer functions.

Due to these difficulties, no attempts have been made to explore the acoustic properties of the circuit-breaker analytically. However, it is considered to be of the utmost importance to have a qualitative picture of these matters. In particular, knowledge about where sound is generated and how it propagates during operation of the circuit-breaker is a prerequisite for a correct interpretation of any signature abnormalities.

The acoustic properties of steel and aluminium are in general characterized by high sound velocity (several kilometers per second) and low attenuation. The circuit-breaker also has large non-metallic parts (porcelain and fibre-reinforced polyester), but the acoustic properties of these materials were found to be essentially similar to the rest and do not seem to require any special attention.

An important advantage associated with acoustic methods is that they are virtually immune to electromagnetic noise. Moreover, external acoustic noise such as traffic and power frequency transformer noise was not picked up to any observable extent. The signal-to-noise ratio was typically as good as 60 dB, both when operating in the laboratory and in a substation.

Fig. 1 shows acoustic signatures from opening of the circuit-breaker. The signals were obtained with three accelerometers

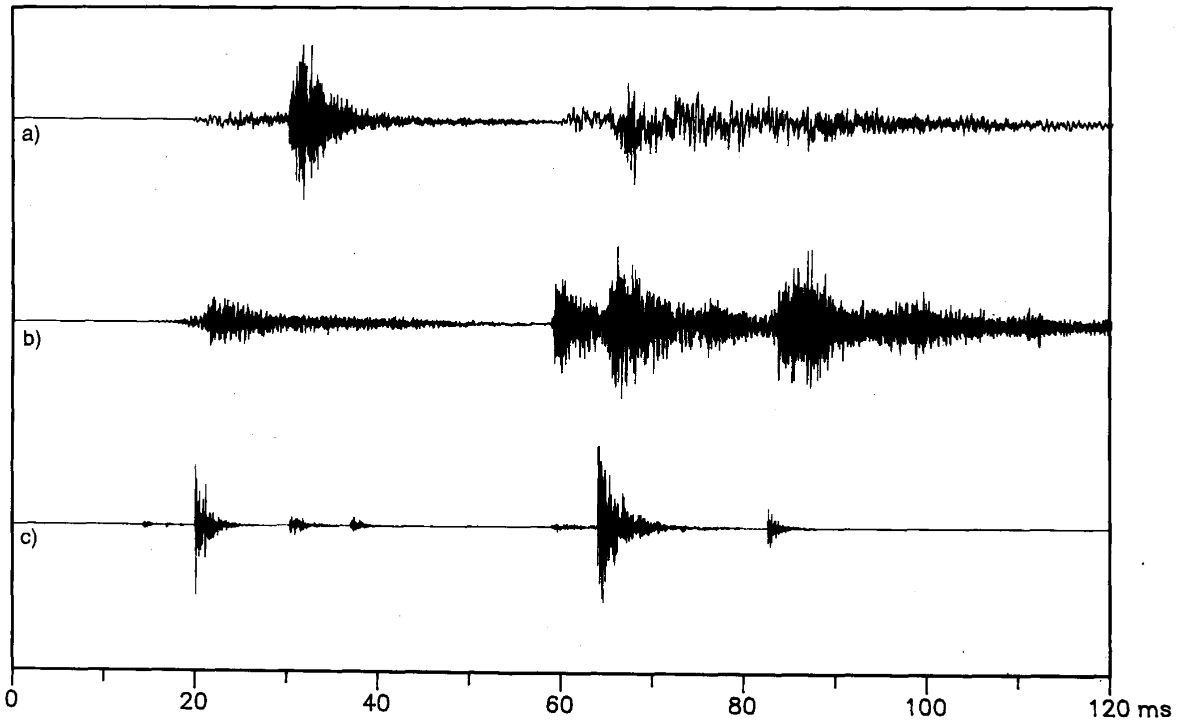

Fig. 1. Synchrone acoustic signatures recorded with accelerometers at the pole (a), (b) and in the driving mechanism (c).

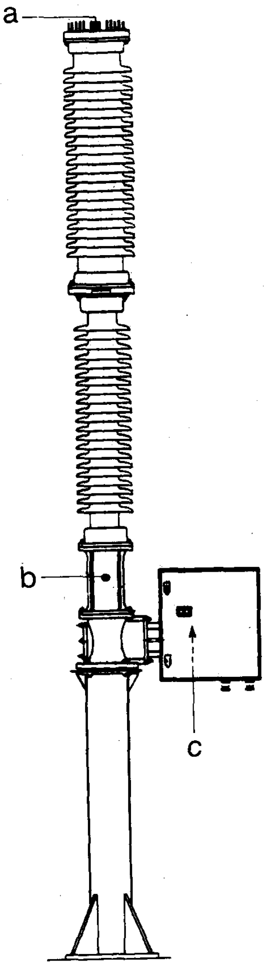

Fig. 2. Location of the accelerometers on the top of the pole (a), on the crank housing (b) and in the driving mechanism (c).

placed at three different locations: on the top of the pole, on the crank housing, and in the driving mechanism, see Fig. 2. As can be seen, great differences exist between these signatures, although they are recorded simultaneously.

The signatures obtained on the pole, Figs. 1(a) and 1(b), appear to consist of only a handful of transients or acoustic events, each lasting for around ten milliseconds or more. In contrast, the signature from the operating mechanism, Fig. 1(c), is composed of nearly ten different transients. The latter events are characterized by a steep front and a duration of only a few milliseconds.

In several ways these signatures contain information about how the circuit-breaker is constructed and also how it operates. The large number of events in Fig. 1(c) indicate that the release of the spring and resetting of the various mechanical locks and relays are rather complex operations. Furthermore, the resulting acoustic events are short, and the resonance frequencies measured in the signal decay are rather high, typically around 10 kHz. This shows that the geometrical dimensions of the parts involved are small. Signatures obtained from the pole contain fewer events because fewer mechanical operations occur here during switching. Furthermore, the pole is built up of large parts (the porcelain tubes etc.) giving resonance frequencies of only a few kilohertz and longer decay times. Figs. 1(a) and 1(b) illustrate these features well.

Intercomparison between the traces of Fig. 1 shows that the acoustic coupling between the various parts of the breaker is rather weak. A strong acoustic signal can be recorded at one location, while almost nothing is heard at the same moment at the two other accelerometer locations. For example, the major event that appears after 32 ms in Fig. 1(a) is hardly visible in Figs. 1(b) and 1(c).

The weak acoustic coupling is a great advantage in this context because it makes it far easier to identify the sources of the individual acoustic events. The events within a signature are clearly separated, and there is an indication of the distance to the source. Sources close to the sensor have large amplitudes, short rise-times and in general much energy in the high frequency range.

Tests have shown that proper location of three accelerometers per pole makes it possible to distinguish more than a dozen events in an opening or closing signature, only by considering the time-domain signals. Furthermore, by carefully studying the construction and working principle of the circuit-breaker, the sources (i.e., the sound-generating mechanical movements) to most of the acoustic events can be identified.

A few examples of corresponding acoustic and mechanical events from a closing of the breaker is given in Fig. 3. In order to support and illustrate this further, two additional traces are included. Fig. 3(a) shows the output from an optical device fixed to the shaft between the driving mechanism and the crank housing. This device gives one voltage pulse per 1.9 degrees of rotation, and the trace indicates when this shaft and thus also the lower contact is moving. Fig. 3(b) shows an electric signal that displays whether the contacts are open or closed.

By comparing these two traces with the acoustic signatures in Figs. 3(c) and 3(d), the origin of several of the acoustic events becomes evident. For example, the burst recorded at the pole after 70 ms is obviously caused by the contacts meeting.

## SIGNAL PROCESSING

### General

The computer programmes that extract, compare, interpret, and present the information from the acoustic signatures are perhaps the most important, but also the most complicated part of an acoustic diagnosis system. In particular, the routines that search for discrepancies between two signatures must be carefully designed. The essential problem is to achieve high sensitivity while minimizing the number of false alarms.

In this work, digital signal processing algorithms well known from speech processing and recognition are applied. The reason for doing so is simply that the problems that arise in the present

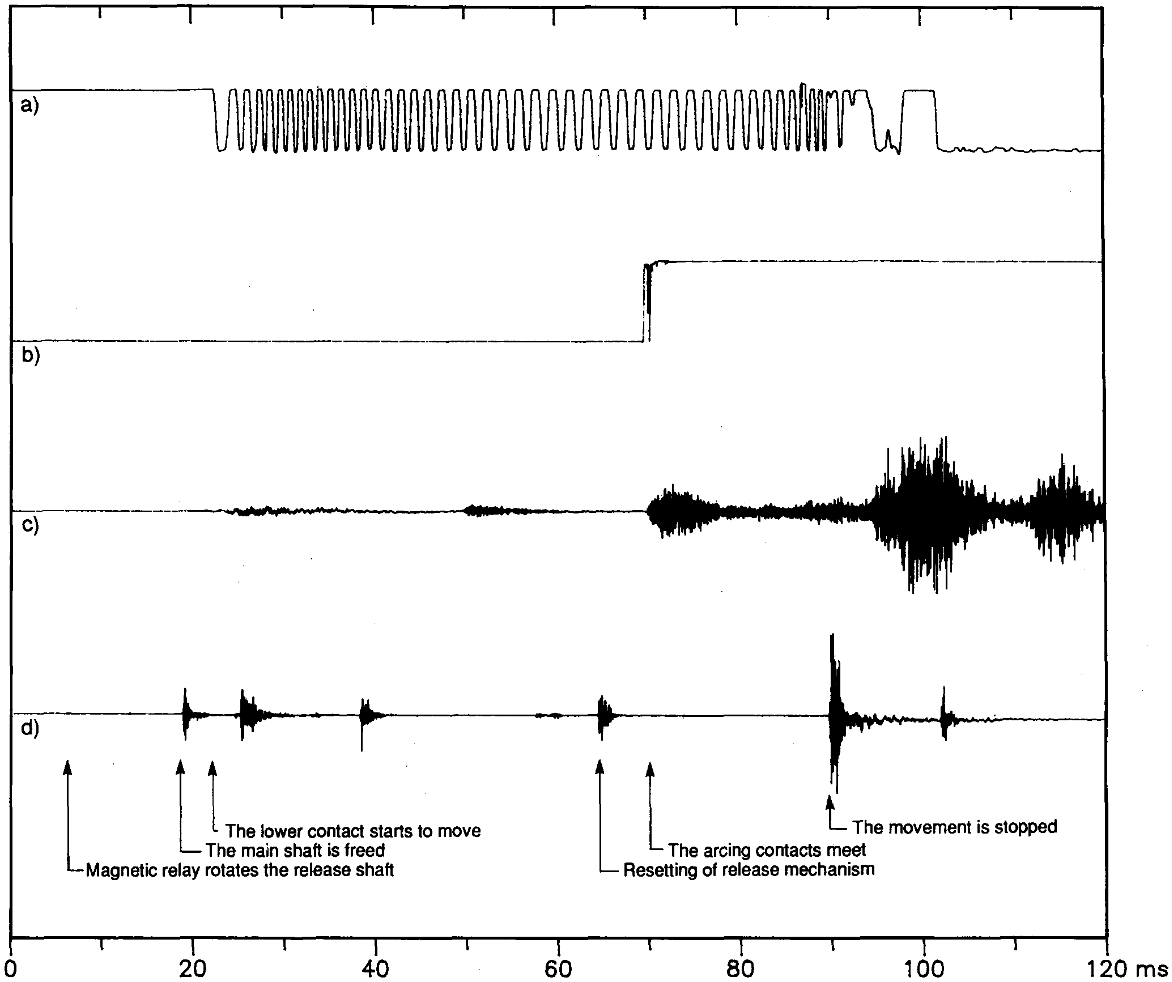

Fig. 3. Synchrone traces showing contact movement (a), contact mating (b), acoustic signatures from the pole (c) and from the driving mechanism (d).

context are very much the same as those faced in speech recognition. The most important similarities are:

- In both cases the main task is to compare two time-domain signals consisting of a number of transients. In speech each transient corresponds to a speech sound (phoneme). In a circuit-breaker signature the transients correspond to mechanical events as discussed earlier.
- The rate at which these individual events appear can vary, but their order is unaltered. In the case of speech recognition, this corresponds to different speech rates. For circuit-breakers the switching-time for one model can typically vary as much as 5%. Hence, in both cases an alignment of the time-axis must be carried out before the signals can be compared.

There exist a large number of advanced techniques for analyzing and characterizing transient signals of these types. In this work the most straightforward method has been applied, namely to consider the frequency vs. time relationships of the signatures. In other words, the events are characterized by their frequency content.

Fig. 4 shows the signal processing schematically. The various parts are explained in the following sections.

### Time/frequency representation

The time-domain signal is divided into overlapping frames of 128 samples. Sampling at 15 μs intervals, this yields a frame length of 1.92 ms. The frequency content of each frame is determined by a Fast Fourier Transform (FFT) using a Hanning window. The window is moved 67 samples before the next FFT is performed. Hence, the time resolution is about 1 ms.

This procedure yields a set of 64 complex frequency components per millisecond, which are combined to ten frequency bands, ranging from 0 to 33 kHz. To assure that weak events also contribute, the frequency components are given in a logarithmic scale.

Hence, the signature is represented by a ten-dimensional frequency vector for each millisecond. Compared to the original time-domain signal, a compression of the information from 134 bytes (67 samples of two bytes) to 20 bytes per millisecond has been achieved.

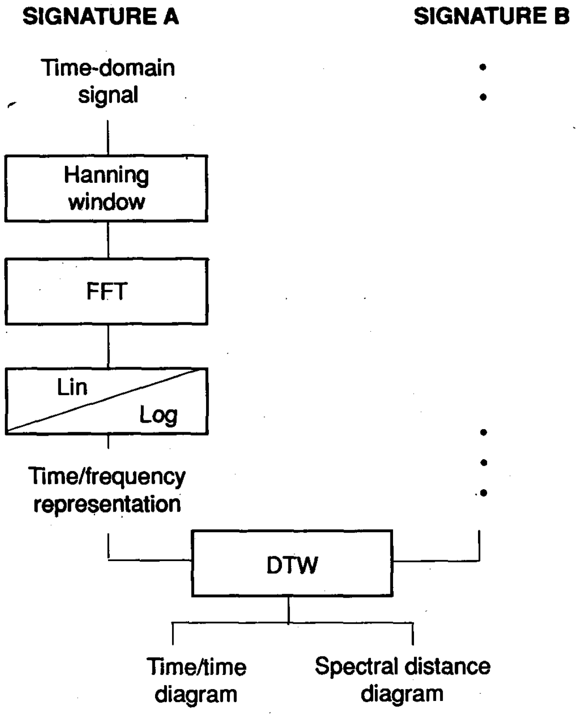

Fig. 4. Signal processing system.

The memory needed for storing four opening and four closing signatures per pole of a three pole breaker adds up to about 60 kbyte. Consequently, a complete set of signatures for some 20 three-pole circuit-breakers can be stored on a 1.2 Mbyte floppy diskette.

### Alignment of the time-axes

Before the frequency patterns of two signatures can be compared, a rescaling of the time-axes is necessary in order to assure that corresponding events are compared. A direct, millisecond by millisecond examination of the differences between the two signatures usually yields large discrepancies. The reason for this is that the time at which a given event appears is not exactly the same for two circuit-breakers. Even for repetitive operations of the same pole this deviation can exceed the length of an event.

The technique used to synchronize or align the time-axes of the two signatures is called Dynamic Time Warping (DTW) and is well known in speech recogniton. Only a brief discription is given here, details are given in textbooks [4].

To find corresponding events in the two signals, a measure of similarity between the frames of the signals must exist. In this work the Euclidian distance between the frequency vectors is used. By applying this measure, the DTW algorithm align the two signals in such a manner that the accumulated Euclidian distance between the frequency vectors of the two signatures is minimized. The resulting optimum time alignment can be visualized by plotting the path of corresponding frame numbers in a time/time diagram.

### Spectral distance

The DTW finds the path in the time/time diagram that gives the lowest accumulated difference between the frequency vectors of two signatures. For diagnostic purposes, however, it is also of great interest to know how this discrepancy is distributed in time. The presence of an abnormal event in one of the signatures will increase the spectral distance at the time this event occurs.

The spectral distance between two corresponding frequency vectors (after alignment) calculated from the ten frequency bands is expressed in dB.

## NORMAL SIGNATURE DEVIATIONS

The questions usually raised in connection with various diagnostic methods of power apparatus appear also when dealing with acoustic diagnosis of circuit-breakers: Which features of the acquired signals contain reliable information about the component, and which do not? What are results of natural, statistical scattering? What is imposed by external parameters such as for example temperature variations?

Thus, the essential, but very difficult problem also in this case is to draw the line between signature deviations that are a result of abnormal conditions, and those that are not. In order to clarify some of these relationships, a large number of tests on circuit-breakers in normal condition (without defects) has been carried out. A few results are presented in the following.

Figs. 5(a) and 5(b) presents time/time and spectral distance diagrams based on two operations (referred to as A and B) of the same circuit-breaker pole. For perfectly synchronous signatures the time/time calculation shall give a linear diagonal (all events occur at the same time). As expected, this is nearly the case here. Only small excursions from the diagonal exist. Fig. 5(b) shows that the deviations between the two signatures is evenly distributed and usually between 2 and 4 dB.

The driving mechanism of this circuit-breaker is able to perform an OUT-IN-OUT sequence without reloading the spring. The signatures obtained during the first and second OUT operations of such a sequence are compared and the results are given in Fig. 6.

As can be seen from Fig. 6(a), the events in the second OUT (where the spring is not fully loaded) are lagging behind the first OUT from about 20 ms. At the end of the operation the delay is about 10 ms. However, the difference in frequency content as shown in Fig. 6(b) is only slightly larger than that of Fig. 5(b). This demonstrates that the DTW works as intended. The time-axes in the case presented in Fig. 6 have obviously been rescaled correctly so that the right events have been compared, yielding a deviation not dramatically different from the synchronous case shown in Fig. 5.

Comparison of the signatures from different poles of the same circuit-breaker type yields somewhat larger discrepancies than when repetitive operations of one pole is compared. This is illustrated in Fig. 7. The time/time diagram shows some excursions from the diagonal, and the spectral distance is typically about

2 - 6 dB. This indicates that every pole has its own, unique acoustic signature, slightly different from other poles of the same model.

The reproducibility of the acoustic signals is good. Removal and remounting of the accelerometers between repetitive operations do not influence the results. Moreover, no effects are observed by interchanging accelerometers of the same type or by locating them slightly (a centimeter or so) out of position.

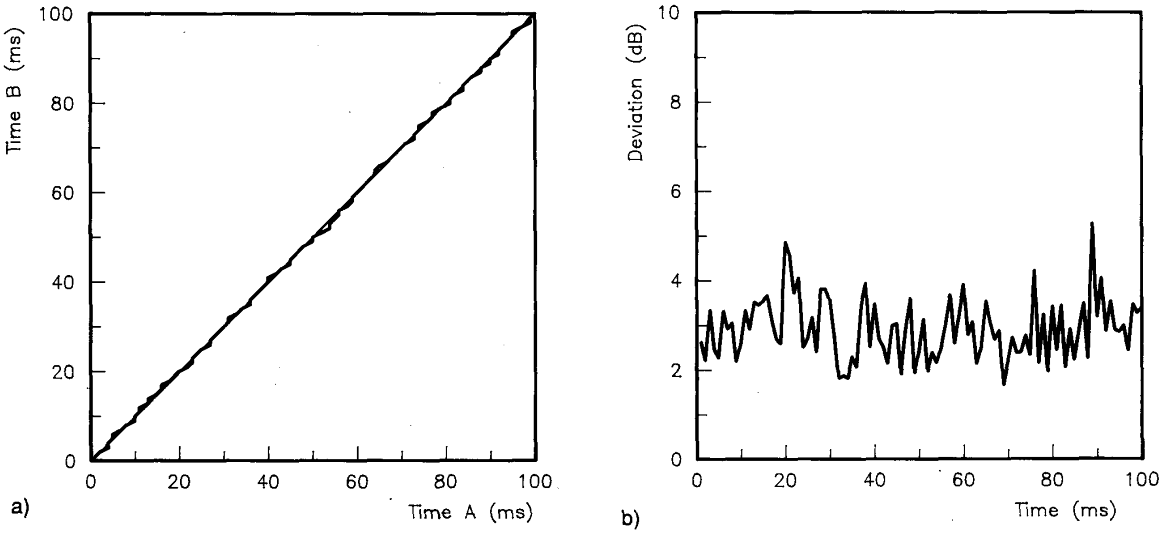

Fig. 5. Time/time (a) and spectral distance (b) diagrams from comparison of two opening operations of the same pole. The accelerometer was located on the top of the pole.

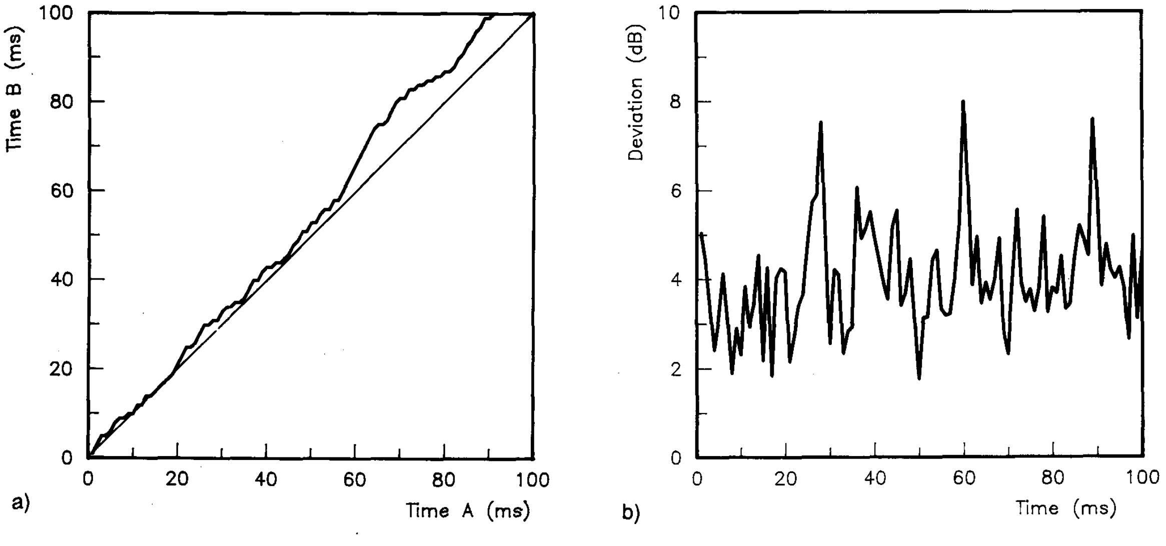

Fig. 6. Time/time (a) and spectral distance (b) diagrams from comparison of two opening operations of the same pole, but with differently loaded spring. The accelerometer was located on the top of the pole.

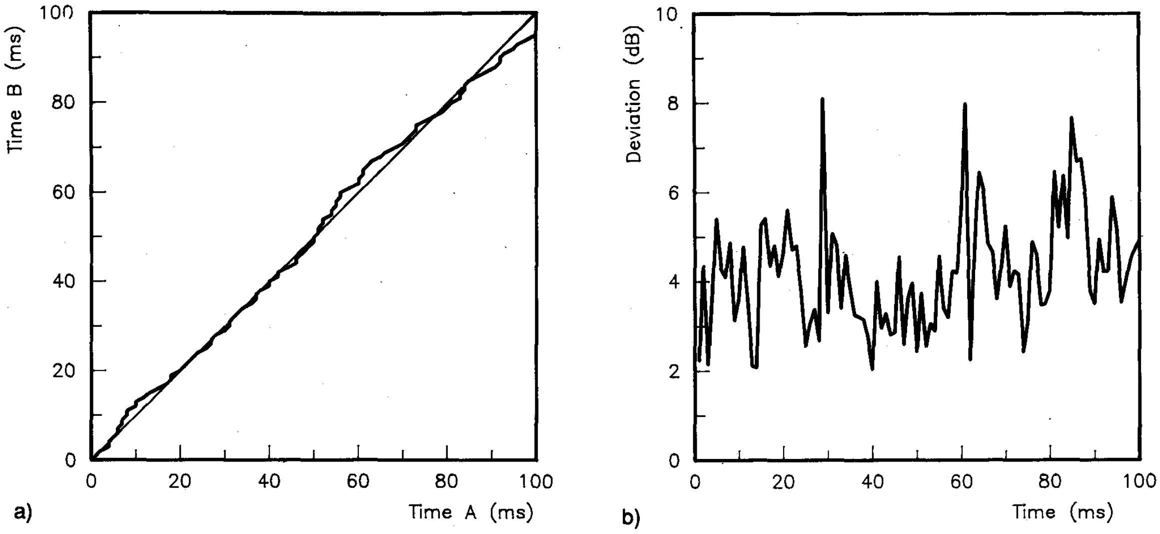

Fig. 7. Time/time (a) and spectral distance (b) diagrams from comparison of opening operations from two different poles. The accelerometers were located on the top of the pole.

## CIRCUIT-BREAKER MALFUNCTION: DEFECTIVE RELEASE MECHANISM

### Description of the fault

The BBC ELF circuit-breaker can be operated both electrically and manually. In the case of electric operation, a command signal is sent into a magnetic relay, and the core of the relay rotates a shaft, which in turn releases the main spring.

In one of the poles installed in the lab the electric release mechanism gradually ceased working after about two hundred operations. Initially, the fault was evidenced by the breaker occasionally not responding to the electric command signal for closing. This malfunction gradually appeared more frequently, and after about five hundred operations the electric closing mechanism did not work at all. From then on closing of this pole had to be initiated manually.

Close investigation of the parts that constitute the release mechanism revealed that the shaft did not revolve enough to free the spring. It seems that the malfunction was due to insufficient lubrication. Nevertheless, this is a serious fault, as it renders one pole of the circuit-breaker inoperative.

### Response of the acoustic diagnosis system

Fig. 8 shows two acoustic signatures obtained at the same location in the driving mechanism of this pole. Trace A (Fig. 8(a)) was recorded when the breaker was new, while trace B (Fig. 8(b)) was recorded when the fault was in an early stage, i.e., after around two hundred (non-energized) operations.

Except that trace B is somewhat delayed compared to trace A, no obvious discrepancies appear between these signatures. The delay between these repeated closings is not larger than what the manufacturer considers as normal deviation between the tripping or closing times for the three poles of a bay.

The signatures were then processed as previously described, Fig. 9 showing the resulting time/time and spectral distance diagrams. From Fig. 9(a) it is clearly seen that the delay of trace B occurs after around 10 ms of the closing. From about 15 ms on the time/time curve is parallel to the diagonal and constantly about 5 ms off, indicating that no further delays occur.

The deviation plot, Fig. 9(b), discloses a major signature difference between 5 and 10 ms. For the rest of the time only insignificant discrepancies are seen.

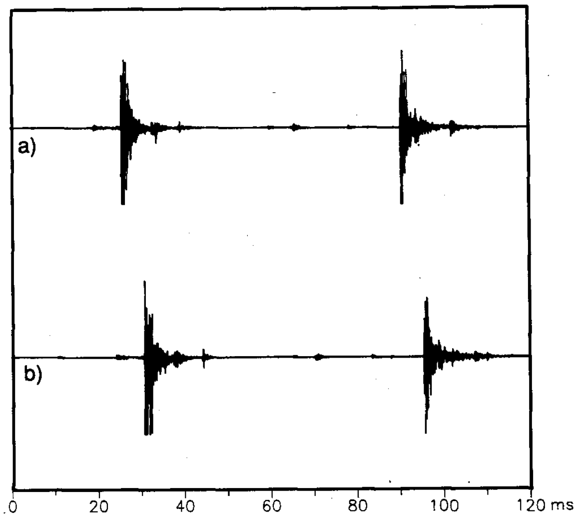

Fig. 8. Acoustic signatures from closing obtained when the breaker was new (a) and after about 200 operations (b).

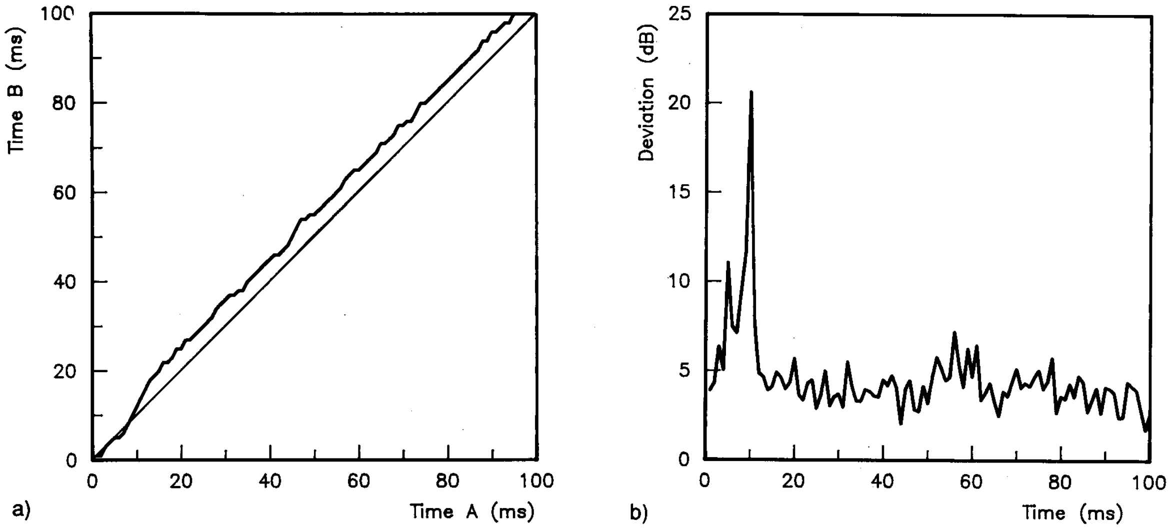

Fig. 9. Time/time (a) and spectral distance (b) diagrams obtained by comparing the signatures in Fig. 8.

By carefully re-examining the time-domain signatures shown in Fig. 8 the cause of the large peaks can be found. Fig. 10 shows the first 30 ms of the signatures with the vertical axis magnified 32 times. Trace B appears to contain an "extra" event after about 5 ms. In addition, it seems like the second event in trace B differs significantly from the first event in A. From then on the signatures are equal.

In addition to these signatures obtained in the driving mechanism, signatures were simultaneously acquired from two locations on the pole. The time/time diagrams calculated by comparing the other channels are similar to that shown in Fig. 9(a). The spectral distance on the other hand, was in both cases low at all times.

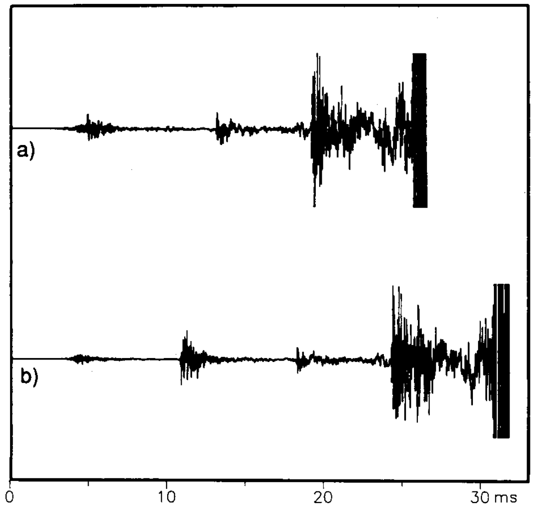

Fig. 10. Close-up of the first 30 ms of the signatures shown in Fig. 8.

### Interpretation

The fact that the extra event occurs after only 5 ms unambigously shows that it originates from the release mechanism. Earlier investigations (see Fig. 3) have shown that the movement of the core of the relay generates sound that can be registered several places in the driving mechanism. This is in fact the only acoustic event that has been detected in the entire circuit-breaker so early in the switching process. Thus this signature analysis clearly indicates an abnormality in the release mechanism.

It is important to recall that this malfunction could be detected at a very early stage. At the moment the abnormal signature was recorded, the circuit-breaker was considered as being in an excellent condition. A conventional inspection, i.e., a visual examination of the driving mechanism, measurements of opening and closing times and contact resistance, would hardly disclose any irregularities. A 5 ms longer closing time would probably be regarded as being a somewhat large deviation, but would hardly lead to a complete overhaul.

## DISCUSSION AND CONCLUSIONS

This work shows that the acoustic signals generated during non-energized switching of a live-tank circuit-breaker can be used for diagnostic purposes. The reproducibility is good, the signal-to-noise ratio is excellent and the mechanical operations generating the different acoustic events are readily identified. Similar conclusions appear in a recently published paper by Park et al. [5], dealing with acoustic diagnosis of oil dead-tank circuit-breakers.

The transient signals generated in a switching operation resemble in several ways speech. Consequently, digital signal processing techniques derived from speech analysis are well suited for analysis and comparison of the breaker signatures.

Parallel to the work described in the present paper, a technique for assessing the condition of the contacts by considering contact resistance fluctuations during switching has been developed. Details will be given in a future paper. By combining the dynamic contact resistance measurements with the acoustic methods, a powerful diagnosis system may be established.

Such a system includes all features of the commonly used conventional non-invasive methods used for checking of circuit-breakers, i.e., contact resistance and switching time measurements. In addition, comprehensive and detailed information about the mechanical condition of the breaker is provided, as for example the defective release mechanism discussed earlier.

Future work will include acquisition and analysis of signatures from a considerable number of circuit-breakers in the Norwegian grid. The quality of a diagnostic system can only can be assessed after several years of field experience. However, the results from tests both in the laboratory and in a switch-yard are promising.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] "Dielectric diagnosis of electrical equipment for AC applications and its effects on insulation coordination", report presented by WG 33/15.08, CIGRE, 1990.

[2] A.D. Stokes and L. Timbs, "Circuit-breaker diagnosis", CIGRE 1988, paper no.13-03.

[3] M.L. Lai et al., "Mechanical failure detection of circuit breakers", IEEE Trans. Power Delivery, vol.3, pp. 1724-1731,1988.

[4] D. O'Shaughnessy, Speech Communication, New York, NY: Addison-Wesley, 1987.

[5] S.Y Park et al., "Measurements for noninvasive mechanical diagnostics of power circuit breakers", Electric Power Syst. Res., vol. 19, pp. 1-10, 1990.

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## Discussion

**S. A. Boggs,** (Underground Systems, Inc., Armonk, NY): The authors are congratulated on a very interesting paper which contributes significantly to the state-of-the-art. The authors have shown that, in retrospect, they could identify a dangerous condition in a circuit breaker using their non-invasive acoustic technology. Thus they have demonstrated the ability to raise an alarm upon detection of a change in, or, perhaps, an absolute value of breaker characteristics associated with a pathological and dangerous condition. However, the obvious question which they leave unanswered for the time being is the likely false alarm rate of a system based on such non-invasive technology. To take the condition discussed by the authors, how often might a temporary burr develop within the mechanism and cause some similar change in the operating characteristics until the burr is worn or broken off by breaker operation. Having too sensitive a diagnostic for a breaker might be like having too sensitive a diagnostic for cancer. You may find that abnormal conditions are, in fact, the norm, and the problem is distinguishing those which will develop into dangerous pathological conditions from those which are self-curing. As with any diagnostic system, the user is not likely to tolerate a false alarm rate which exceeds the actual problem rate. Given the exceptional reliability of modern breakers, the false alarm rate would have to be extremely low.

One can look at the general problem of breaker maintenance scheduling from another perspective. Modern breakers are generally rated for a fixed number of mechanical operations (ranging from several thousand for high voltage puffer breakers to ten thousand or more for lower voltage vacuum breakers) or for a limited fault current interrupting duty. However, present breakers have only a mechanical counter for operations. Thus the station maintenance function has no way of knowing the fault interrupting duty of the various breaker poles. As most faults are single phase, one phase of a breaker pole could have seen a much greater fault current interrupting duty than the other poles of a breaker position. The statistical variation of interrupting duty will tend to increase as the mean of the fault current distribution increases relative to the breaker rating, so that a relatively few fault interruptions can use up the interrupting capability of a breaker pole.

An alternative approach to the authors' operational monitoring system is an ampere cycle accumulator, which maintains a running tab of the breaker interrupting duty. This, along with the existing mechanical operation counter, provide the information necessary to determine which breakers poles are due for maintenance. About ten years ago, while working at the Research Division of Ontario Hydro, I conceived and contributed to the development of such a device. This small, microprocessor-based device was powered by the DC station supply with battery backup for the stored data. The device integrated the current flowing through each breaker pole from a settable time after trip (to allow for the time from trip to contact separation). The signal to be integrated came from a CT core on each pole. A few samples were installed at an Ontario Hydro GIS, but the device was not widely deployed, as the cost to Ontario Hydro of altering its station drawings was in the range of $5000 per breaker, much more than the cost of the device. However, if integrated with breaker manufacture, the device would add only a few hundred dollars to the cost of a breaker. The device was offered to the major manufacturers of the time (ASEA, BBC, and Siemens), but it was apparently ahead of its time. Now that the manufacturers realize that unnecessary breaker maintenance both reduces the reliability of the breaker and increases the cost of ownership, providing a rational basis for scheduling maintenance appears to have an increased priority among the breaker manufacturers. The obvious question is whether the decision to maintain should be based on non-invasive diagnostics, as the present authors suggest, or on breaker operating duty as determined by a device such as the ampere cycle totalizer. The authors' comments on this dilemma would be most welcome.

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**M. RUNDE, T. AURUD, L.E. LUNDGAARD, G.E. OTTESEN and K. FAUGSTAD:** The authors would like to thank S.A. Boggs for his interesting questions and comments.

His first question about the risk of getting an unacceptable high "false alarm rate" when using very sensitive diagnostic methods is highly relevant, and we share his concerns on these matters. The credibility of a diagnostic system that signals abnormal conditions more frequently than the actual problem rate will certainly diminish over time.

However, it should be emphasized that the proposed system is intended for periodical use, for example on a yearly basis. It is not an on-line, automated system for continuously monitoring with all the possibilities for false alarms inherent in such systems. Provided that the acoustic signatures are examined and interpreted carefully, we think that a substantial amount of information on the condition of a circuit-breaker can be obtained.

But again, we agree that the ability to distinguish between natural variations in the signatures and deviations induced by flaws is crucial to this technique, and that this ability has not yet been demonstrated properly. Acquisition and analyses of signatures from a large number of circuit-breaker in the grid are now under way, and hopefully this work will clarify and demonstrate the reliability of the proposed diagnostic method.

The second issue raised by the discusser deals with the accumulated interrupted current as a measure of the condition of a circuit-breaker. It is well-known that contact erosion increases rapidly with the magnitude of the interrupted current, so one possible way to assess the condition of the contacts is to keep track of the breaker operating duty. This can be done by installing the ampere cycle accumulator device referred to by the discusser. A much cheaper alternative is to use the interrupted current recordings already available from the existing current transformers. This is the present practice in several Norwegian substations, and circuit-breaker maintenance is scheduled partly on basis of the accumulated interrupted current.

However, as a mean for evaluating the overall condition of the entire circuit-breaker we feel that the accumulated current approach might have severe limitations. According to CIGRE statistics [1] most circuit-breaker malfunctions are of mechanical origin and most of these are not necessarily related to high interrupted currents. Abnormal conditions like poor lubrication, misalignment of the contacts, flaws in the triggering or driving mechanisms, deviation in switching times between the phases, broken parts, loosened bolts, etc., will not be revealed by use of an ampere cycle accumulator.

### Reference:

1. G. Mazza and R. Michaca (WG 13-06), "The first international enquiry on circuit-breaker failures and defects in service", Electra, no. 79, Dec. 1981, pp. 21-91.

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