# Continuous Monitoring of Circuit Breakers Using Vibration Analysis

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*Abstract*—**This paper reports the results from three years of continuous condition monitoring of high-voltage circuit breakers (CBs) using vibration analysis. More than 1000 vibration patterns from the operating mechanism of three different spring-operated $SF_6$ breakers in normal service are analyzed. The patterns are recorded during each opening/closing operation and compared with references to identify timing and frequency deviations. Two of the three investigated CBs were operating well, while the third suffered from several severe problems. A developing failure that caused this breaker to not open on command was identified in advance. The reproducibility of the vibration patterns is high for a faultless CB and this makes it possible to separate faulty conditions from natural variations. The vibration analysis method is, however, dependent on a well-conditioned vibration pattern without noise and with distinct events. If the instrumentation is made sufficiently robust to withstand both the electrical disturbances in a substation environment and the mechanical shocks during CB operation, vibration analysis seems to be a promising technique that can be used on a continuous basis to detect malfunctions in the operating mechanism.**

*Index Terms*—**Circuit breaker (CB) testing, high-voltage techniques, vibration measurements.**

## I. INTRODUCTION

MECHANICAL malfunction of the operating mechanism is by CIGRÉ WG 13.06 [1] reported to be an important failure mode for high-voltage circuit breakers (CBs). Vibration analysis is an advanced diagnostic technique suitable for detection of such failures [2]–[9]. Poor lubrication, slow relays and latches, malfunction of shock absorbers, etc. are typical problems that can be revealed by the method. With a detailed knowledge of the CB (i.e., information about when various parts operate in time during opening/closing of the breaker), it is possible to identify which subcomponent failed. In [7], 93 CBs in presumably healthy conditions were tested with vibration analysis and several serious faults were identified, including lubrication problems, and an incorrectly assembled crank. Both of these faults were introduced as a result of normal periodic maintenance. In [5], [7], and [10], the vibration analysis based on Fourier transformation and dynamic time warping [11] is used. Alternative analysis methods reported in [12]–[14] are based on modal identification and wavelet theory.

A natural extension to periodic testing is to apply vibration analysis continuously to CBs in normal service. In this case, the sensors can only be placed in the operating mechanism on ground potential and information about the main contacts cannot be obtained. A main question is how the acoustic noise from the arc will affect the measurements. If the noise is dominant and significantly dependent on the arc current, continuous monitoring based on vibration analysis is impossible. The results reported in [10] based on laboratory measurements show that acoustic noise from the arc does not interfere with the vibration measurements.

A continuous monitoring system must have a false alarm rate much lower than the CB failure rate. The system should therefore be very reliable and insensitive to natural variations in the vibration pattern from the CB. The purpose of the present work is to study if vibration analysis is applicable for continuous monitoring of CBs in service.

This paper first briefly outlines how the vibration analysis method can be applied to assess the mechanical condition of CBs. Then, the results from three test installations are presented. Finally, the results are discussed together with the fundamental and practical implications.

## II. VIBRATION ANALYSIS

Diagnostic testing by vibration analysis is to compare a vibration pattern recorded during an opening/closing operation with a reference and quantify the difference. Deviations in the vibration signature indicate deviations in the CB condition. Basically, the method used in this paper identifies deviations in timing (occurrence of events) and frequency content. The vibration magnitude, which is the most evident result of the visual inspection of vibration patterns, is of less importance.

The method used here for comparing patterns is briefly described in [5] and slightly modified due to the different sampling frequency (51.2 kS/s in this case). The signal is divided in overlapping frames with 128 samples. The frequency content of each frame is obtained from a fast Fourier transform (FFT) using a Hanning window. This window is moved 51 samples (sampling frequency divided by 1000) before a new FFT is performed, resulting in a resolution in time of about 1 ms. This procedure gives $128/2 = 64$ frequency components that is combined to ten frequency bands (from 0 to 25 kHz) for each millisecond. The calculations then follow [5] using a dynamic time warping method that is widely applied within speech recognition [11]. The final result is the deviations in timing and frequency content as a function of time as shown in Fig. 1.

## III. INSTRUMENTATION

The vibrations are measured by an accelerometer designed for a nominal shock of 5000 g (maximum 50 000 g) and gives out 1 mV/g ($g = 9.81\ m/s^2$). The −3-dB low-frequency point

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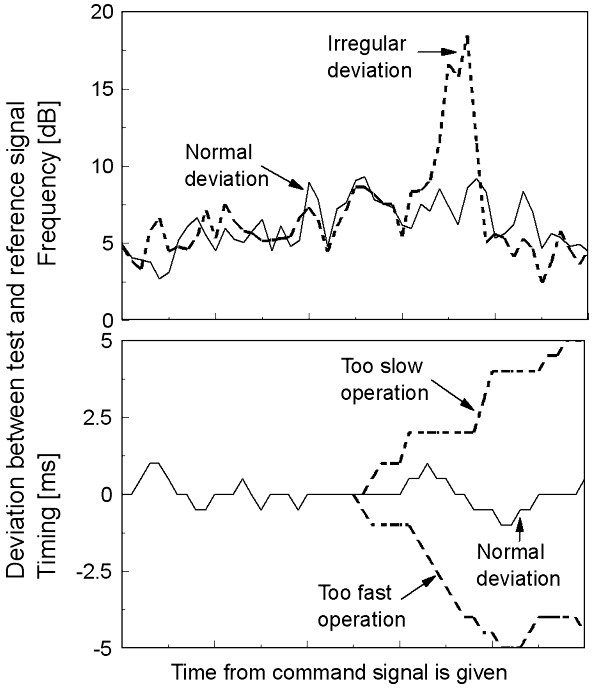

Fig. 1. Typical examples of output from the vibration analysis algorithm: frequency deviation and timing deviation; both as a function of time.

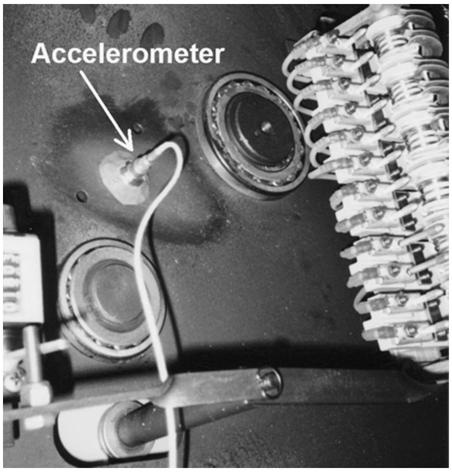

Fig. 2. Example of how the accelerometer is mounted in a 145-kV CB.

is at 0.16 Hz while the natural resonance frequency of the accelerometer is at 130 kHz. In all of the performed tests, the accelerometers were mounted in solid metal in the operating mechanism of the CB in a short distance from the main shaft (Fig. 2). At such a position, most mechanical incidents occurring during CB operation are seen as fairly distinct events in the vibration pattern. The specific accelerometer position is not critical, but if the comparison between phases or units is to be made, the locations should not deviate more than roughly 1 cm. The vibration signal is insulated from the accelerometer chassis and grounded only at the recorder side. To avoid electrical noise and damaging high potentials, it is often necessary to insulate the accelerometer from ground in the CB. This can be accomplished by mounting the accelerometer in a spacer made of a material that is a good acoustic but poor electric conductor. A 1.5-cm-thick piece of a very stiff thermoset polymer was used in the three test installations. This reduces the capacitive coupled noise but still transfers mechanical vibrations well.

The coaxial lead from the accelerometer is connected to a nearby standard preamplifier that biases the accelerometer, filters out the dc voltage, and supplies a longer coaxial cable to an indoor measurement unit. Amplification of the signals was not necessary in the actual setups.

The measurement unit was a four-channel, single-ended, PC-based data-acquisition (DAQ) board with 16-b vertical resolution and a built-in antialiasing filter. The DAQ-card was triggered digitally based on the command signals to the CB. The open and close command signals are converted to a common transistor-transistor-logic (TTL) signal using optocouplers with sufficient insulation level to withstand possible overvoltages. If the analog vibration pattern itself triggers the DAQ card, possible, initial delays are not detected.

The outdoor temperature was for two of the three test installations measured by a thermo element connected to the forth cannel of the DAQ card.

The vibration patterns were recorded with a sampling rate of 51 200/s for a period of time up to 150–250 ms. The PC program stored the vibration patterns in unique raw data files and compared them with the references. A comparison with both the opening and closure references was performed for the first channel. The result with the smallest deviation was chosen and this also identified CLOSE or OPEN. The result of the analysis is a file containing timing and frequency deviations as a function of time for all vibration channel (Fig. 1). Based on knowledge from [5] and [7] a timing deviation exceeding 4 ms and a frequency deviation of 15 dB were considered to be critical and denoted the “alarm limits.”

## IV. RESULTS

This section shows the results of the vibration analysis from the three test installations, partly running in parallel. The three investigated CBs were from different manufacturers, and all were spring operated. More than 1000 vibration signatures are analyzed.

### *A. First Installation*

The first test installation was in service for almost three years. The CB had separate operation mechanisms for each pole, so three vibration signatures were measured on this unit every time the CB operated. The distance from the preamplifier to the recorder was 80 m. The breaker was in service in a 145-kV double overhead line system and in periods it was operated daily. The interrupted current was very limited since it was commutated to the constantly energized parallel line.

The reference vibration pattern for phase A of this CB is shown in Fig. 3. These two fingerprints contain a series of distinct events. The first 100 ms for closing and 90 ms for opening operations were included when the vibration patterns were compared. Similar references were used for the other two phases, B and C.

A total of 322 vibration signatures from 118 CB operations were collected and analyzed (for some of the earlier operations,

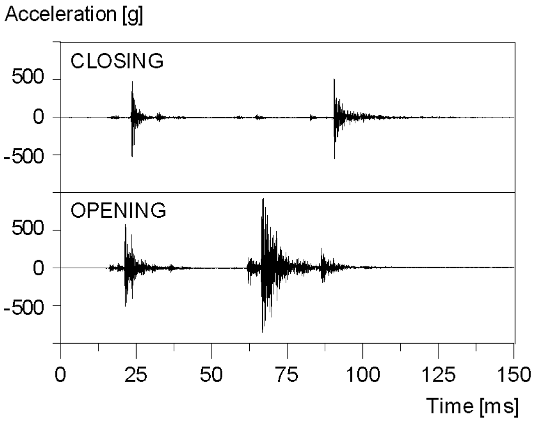

Fig. 3. Recorded reference vibration pattern, phase A. First installation.

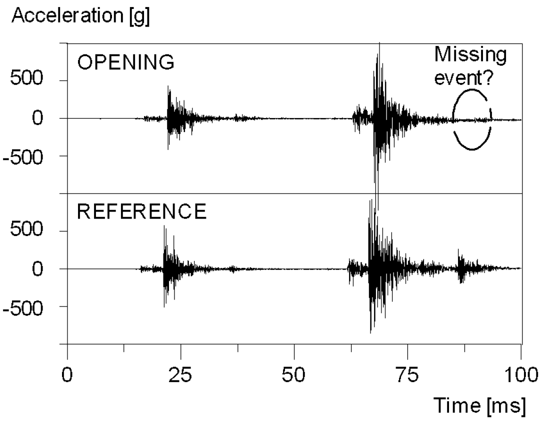

Fig. 4. Vibration pattern of opening operation compared to the referenced two operations before a major failure.

only two of the accelerometers were functioning). Thirteen cases resulted in maximum deviation outside the "alarm limits." Two of these are caused by electrical noise and the rest appear to be caused by real deviations in the CB condition.

In the first year of the test period, the CB once failed to open on command due to a major failure at the main shaft of phase A. This failure was detectable in the vibration pattern two operations prior to the failure as shown in Fig. 4.

In Fig. 4, we see that the final event present in the reference apparently is missing. The analysis program reported this as a large time delay developing at the end as seen in Fig. 5, resulting in an alarm. No alarming values were reported in the frequency deviation implying that the event is really present but reduced and delayed. The following closing operation showed a 10% time delay over the whole time interval, typically caused by a loose spring. The CB then failed to open on command. The CB cabinet was then opened and a part responsible for stopping the rotational movement of the main shaft was found to be broken.

During the first year of installation, some initial, practical problems resulted in low reliability of the setup. Software bugs and subsequent operations of the CB too close in time, as discussed later, mostly caused the problems. After this period, practical trend curves of the maximum deviations could be established as shown in Fig. 6. The maximum deviations from the vibration analysis are presented as functions of the number of the CB operation. The outdoor temperature was also recorded in order to reveal any correlation to timing deviations in the vibration patterns.

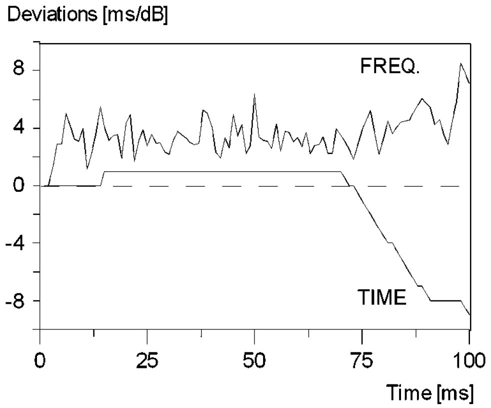

Fig. 5. Timing and frequency deviations from vibration analysis of Fig. 4.

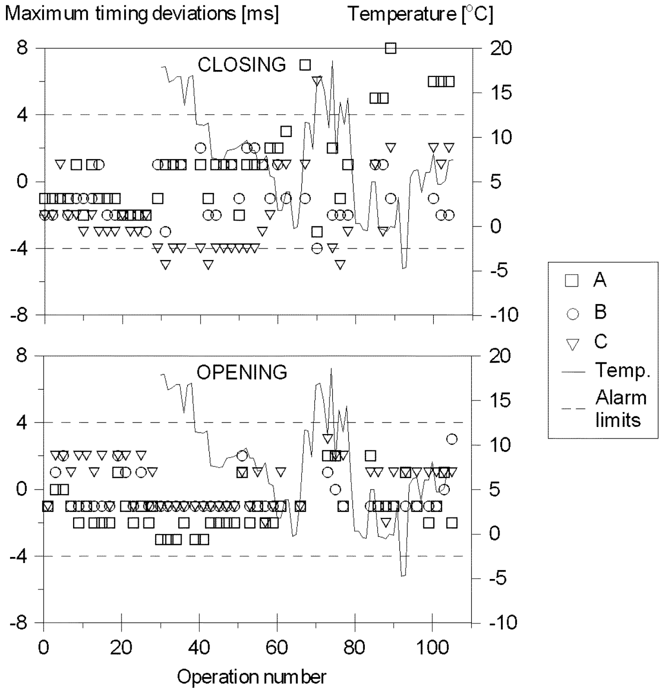

Fig. 6. Maximum timing deviation as a function of the operation number the last two yeas of the test period. A, B, and C are the three phases. Alarm is the initially suggested alarm limit.

For closing operations, there are obviously large and unacceptable timing deviations in phase A and C. The operation seems to be slightly slower in cold weather or when the time between subsequent operations becomes large. There is also a general trend toward slower operation of the breakers in phase A and C. For opening operations, there are no timing deviations that exceed 3 ms compared to the references.

The largest deviation arises in closing operation number 70 caused by three large noise peaks in the vibration signature as shown in Fig. 7. The source of the noise is unknown, but it is not a fault current as initially suspected. In this case, the frequency deviation is actually so large that the analysis program misinterprets it as an opening operation. The deviations compared to the reference for closing operations (obtained manually) are shown

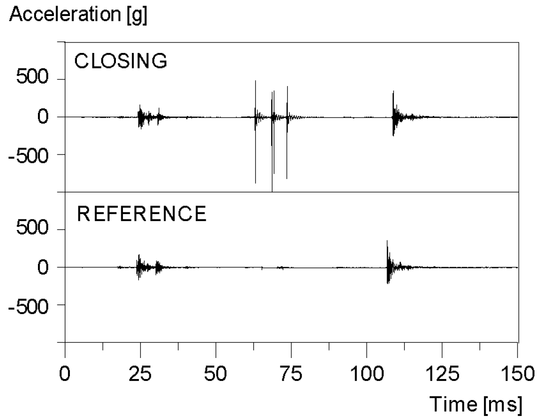

Fig. 7. Vibration pattern with large noise peaks compared to the closing operation reference, phase A.

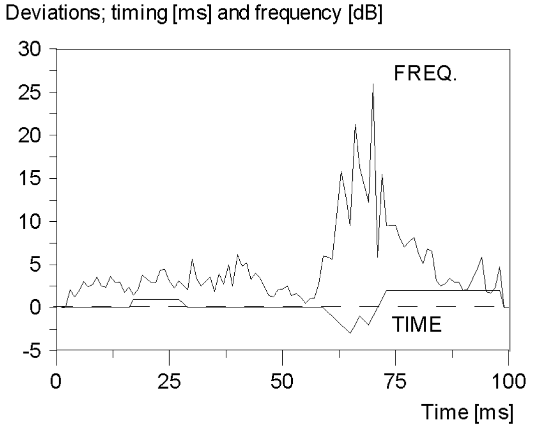

Fig. 8. Timing and frequency deviations from vibration analysis of Fig. 7.

in Fig. 8. The reference is somewhat different than in Fig. 3 since the whole operating mechanism of the CB is replaced due to the fault illustrated in Figs. 4 and 5.

The operating mechanisms of both phase A and C were replaced during the test period. The operating mechanism of phase A failed as identified by the test installation in Figs. 4 and 5. Besides, a tripping coil was damaged in the very beginning of the test period and a complete breakdown of the whole operating mechanism occurred shortly after the test period, both events in the phase C unit. Measurements of the operation times after the last repair of phase C revealed large differences between the phases. Phase A was about 10 ms slower than the other for closing, while the new phase C was 8 ms slower than the others for opening. Two years after the project was finished, phase A of this CB exploded (after a closing operation) for an unknown reason.

### *B. Second Installation*

The second test installation was in service for almost two years. The CB had a common operating mechanism for all poles, and operated a capacitor bank in a 33-kV system. A single vibration signature was measured for each operation of the CB. The unit was located indoor and the distance between the preamplifier and the recorder/PC was about 5 m.

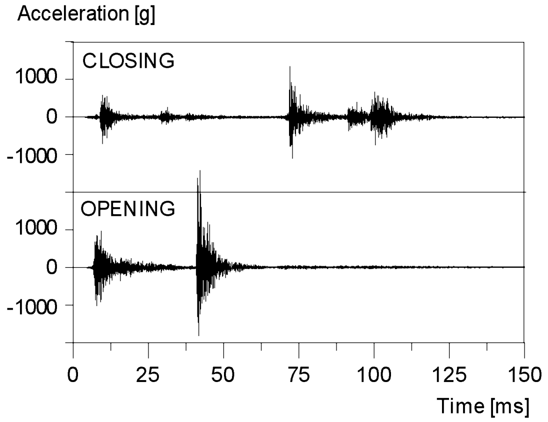

Fig. 9. Reference vibration patterns, second installation.

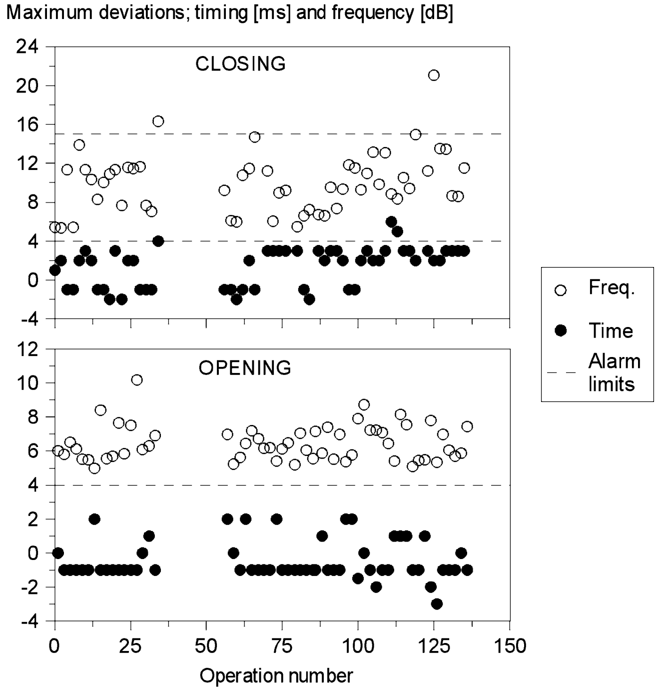

Fig. 10. Maximum timing deviation as a function of the operation number the last year of the test period. The alarm is the initially suggested alarm limit.

The reference vibration patterns for this CB are shown in Fig. 9. These two fingerprints contain a series of distinct events. The first 120 ms for closing and 60 ms for opening were included in the comparison.

As seen from Fig. 9, the vibrations measured during operation of this CB had large amplitudes (above 2000 g during opening). This calls for a robust measurement setup.

A total of 146 vibration signatures are collected and analyzed. Seven cases resulted in a maximum deviation outside the "alarm" limits. Two of these are caused by electrical noise and the rest appear to be real deviations in the CB performance. The vibration signature for closing often had some noise spikes around 62 ms, but due to the short length of the coaxial cable, these spikes were very steep and were thus filtered out by the analysis program.

Fig. 10 shows the trend curves for maximum time and frequency deviation over the last year of operation. Most of the

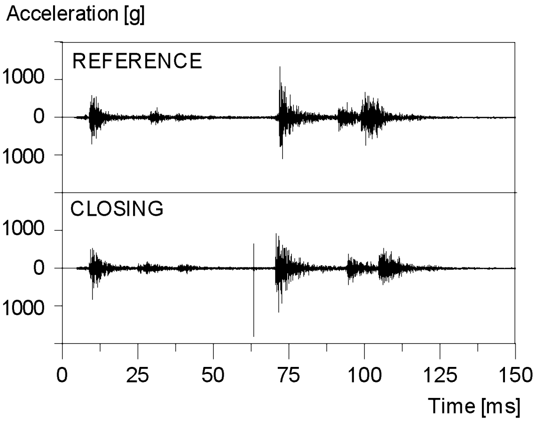

Fig. 11. Upper trace: Reference signal closing. Lower trace: typical closing operation.

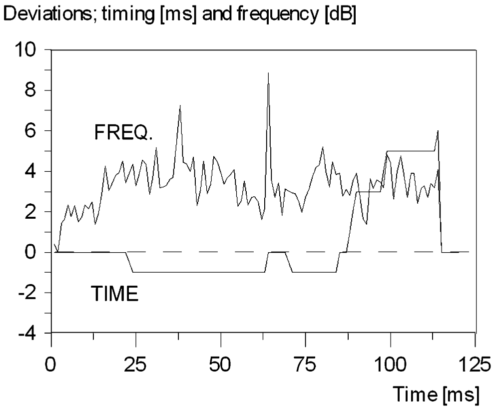

Fig. 12. Timing and frequency deviations from the vibration analysis of Fig. 11.

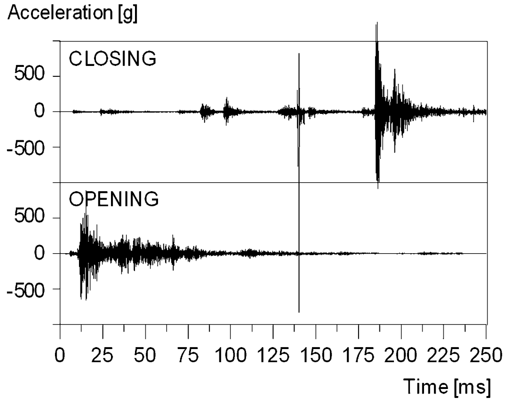

Fig. 13. Reference vibration patterns phase A. Third installation.

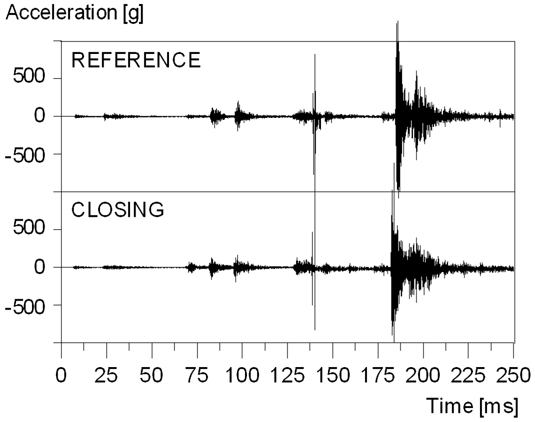

Fig. 14. Upper trace: Reference signal closing. Lower trace: typical closing operation.

timing deviations for the closing operations are caused by a time delay at the end of the operation. This is typical for this CB and in Fig. 11, this can be observed after 80–100 ms. Fig. 11 also shows the noise spike around 62 ms. This spike is very narrow and is mostly filtered out by the analysis program. Fig. 12 shows how the timing deviation develops with time toward the end of the analysis period of 120 ms. At this point, the movement of the main shaft has come to a complete stop, so any developing timing deviations are of less importance related to condition monitoring.

The main challenge with this second installation was the high amplitudes of the vibrations during opening operations. This required a solidly fixed accelerometer insulated from ground since high potentials differences were observed in the grounding system. The CB seems to have somewhat larger natural deviations in timing so the setting of the 4-ms alarm limit should probably be increased. The CB seemed to operate well throughout the whole test period.

## *C. Third Installation*

The third test installation was in service for almost one and a half years. The CB had separate operation mechanisms for each pole, and three vibration signatures were measured on this unit during each operation. The distance from the preamplifier to the recorder was 100 m. The breaker was installed in a 300-kV filter bank and operated regularly twice a day. The outdoor temperature was also measured, but is not presented here since no correlation to timing was found. In the middle part of the test period, the installation was put out of service due to an overvoltage in the command signal causing a breakdown of the optocoupler in the triggering device.

The reference vibration pattern for phase A of this CB is shown in Fig. 13.

The vibration pattern from the closing operation is well defined with several events, in contrast to the signal from the opening operation that contains few events and a rather indistinct ending with a long lasting "ring-down." Analysis lengths of 200 ms for closing and 50 ms for opening were chosen. This type of CB was the newest and has faster opening and slower closing operations than the others.

A total of 585 vibration patterns are collected and analyzed. Fig. 13 shows the two main problems in this third installation. These are the large noise spikes around 140 ms in the closing operation and the indistinct vibration pattern of the opening operation. When comparing the references, this often results in high-frequency deviations of around 140 ms for closing operations as shown in Figs. 14 and 15. For an indistinct vibration pattern, the analysis algorithm tends to falsely report large timing deviations, increasing toward the end of the analysis period.

The trend curves for closing and opening are shown in Figs. 16 and 17, respectively. The empty period between operation 150 and 200 is caused by the breakdown of the triggering device.

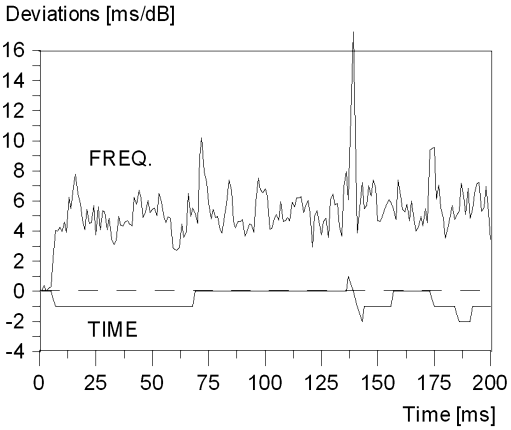

Fig. 15. Time and frequency deviations based on a vibration analysis of Fig. 14. Deviations caused by the noise spike around 140 ms.

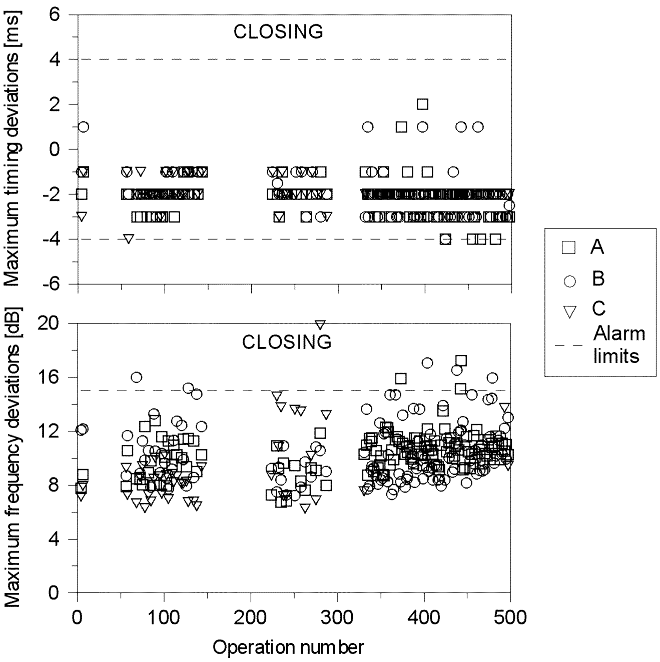

Fig. 16. Maximum deviations as a function of the operation number for the third installation. Closing operations. A, B, and C are the three phases. Alarm is the initially suggested alarm limit.

For closing operations, the noise will, in some cases, result in timing deviations, but in no cases this was outside the alarm limit. For opening operations, the frequency deviation is very limited. The noise spikes present in closing operations result in large frequency deviations. The indistinct vibration pattern of opening operations results in very large timing deviations.

The CB in this third installation seems to be very precise and there are no real deviations in its mechanical condition. The noise spikes and the indistinct vibration pattern are discussed more closely in the next section. The noise spikes were found synchronized in time with a radiated electromagnetic (EM) field in the vicinity of the CB as measured by a loop antenna. This radiated field will induce voltages in the 100-m-long coaxial cables between the sensors and the single-ended recording system.

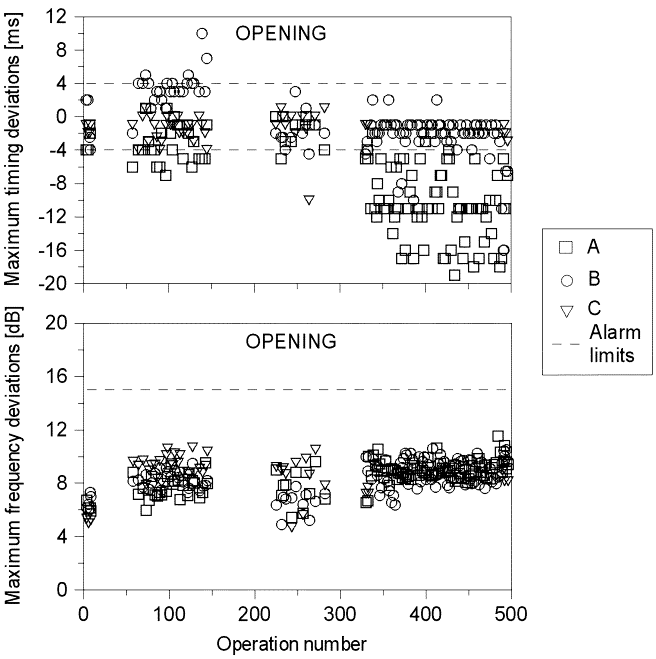

Fig. 17. Maximum deviations as a function of the operation number for the third installation. Opening operations. A, B, and C are the three phases. Alarm is the initially suggested alarm limit.

The source of the radiated field is probably the charging current of the capacitors in the 300-kV filter. No radiated EM noise was observed during opening operations. The effect of the noise spikes is easily ignored by manual inspection and it is thus only the automation that makes this a real problem.

## V. DISCUSSION

The first test installation identified a deviation in the CB condition that later caused the breaker to fail to open on command. The performance of the CB was identified to be poor for phase A and C. Both of these CB poles had severe failures shortly after the investigation was finished. The second installation identified a reliable CB but with larger natural deviations in timing than expected. Accordingly, the alarm limit for timing deviations should be increased. The CB in the third test installation appeared to operate very reliably and no indication of mechanical problems was found.

A fundamental requirement for continuous diagnostic techniques is reliability. False alarms will not be tolerated in a longer perspective. The three test installations have identified two important challenges for continuous vibration analysis on CBs. These are electrical noises in the recordings and implications of an indistinct and diffuse vibration pattern.

- *Electrical noise in the vibration pattern.* This was most dominant in the third test installation with the highest voltage level and the most challenging EM environment. A number of noise spikes were observed at 140 ms. A very important point is, however, that the noise is limited to a short period at the same location in time for all closing operations. This enables two solutions: One is to modify the analysis program to ignore the vibration pattern where the predefined noise is located.

The other is to improve the (single-ended) acquisition technique used in the three test installations. A differential amplifier and signal transmission system were tested with success at the third installation. The length of the coaxial cables is also of importance. The longer the cables are, the more noise could be induced. Also, a long cable will reduce the steepness of the noise pulses so that the analyzing program does not filter them out. This is seen in the second installation were a 5-m-long cable resulted in relatively few problems compared to the 100-m-long cable at the third installation.

- *Vibration pattern quality*. The algorithm for comparing vibration patterns is dependent on having signals with distinct events. At the end of the analysis period when the operation is completed, the remaining ringing effects (echo) and lack of distinct events can result in large, false timing deviations. Choosing the analysis time with care and comparing the vibration pattern with its reference only as long as distinct events are present solves the problem. Obtaining a vibration pattern with high quality could be a problem for opening of a modern CB. The problem was investigated during this work and ignoring the low part of the frequency response improved the analysis to some extent. But more work has to be done to obtain a complete solution. A solution to this problem could be to simply ignore all opening events and base the diagnosis on closing only. Still, vibration analysis will reveal information on the CB condition.

Both of these two main problems are related to the automated comparison with the references and the interpretation of the result.

Some more practical, but still very important traps have been identified during this work. Simple solutions exist in all cases. These are:

- Noise in the command signal can in some cases result in trigging of the recorder without the presence of a vibration signal. The solution to this is to use an integral criterion for the recorded signal. A recorded signal $u(t)$ should be rejected if $\int_0^T |u| \cdot dt - |\int_0^T u \cdot dt| < \mathrm{elim}$ where *elim* is a predefined constant based on a normal operation and $T$ is the total recording time. This criterion will also eliminate cases when the signal goes constantly high, as is often the case with a permanent contact problem in the measurement system.
- Large time deviations are found when the CB in the first test installation is closed and then opened after a few seconds while the motor charges the main spring. In this case, the motor continues to charge the spring also after the opening operation. The result is a somewhat slower opening since the main spring, which for this type of operating mechanism also contributes to the opening, is charged less than usual. Furthermore, for the same reason, the next closing operation becomes somewhat faster than usual (10% timing deviation was observed). To solve this problem, vibrations patterns too close in time must be rejected. For operating mechanisms where the electrically charged spring only contributes to the closing operation, and a second spring (that is charged by the closing itself) provides all of the mechanical energy for opening operations, operations too close in time are not a problem.
- Overvoltages may occur in the recording system. To prevent damage to the equipment, overvoltage protection should be installed on each channel of the recorder. The accelerometer should be isolated from ground in the operating mechanism and finally an optocoupler with sufficiently high insulation level should be used for the conversion of the command signal (110–220 V) to a TTL triggering signal.
- Robust equipment is required to withstand the high vibrations over time. Fig. 9 shows accelerations above 2000 g. The accelerometer needs to be solidly fixed.

To what extent the vibration signature will be affected when the CB interrupts large short-circuit currents is still uncertain. The preliminary conclusion that the vibration pattern is independent on acoustic noise from the arc is based on laboratory measurements only [10]. None of the CBs cleared any fault currents during the test period.

There are some indications that CBs after a period of inactivity will have slower operation. As a result, the alarm limits must be carefully set, also taking the operational frequency of the CB into consideration.

There are no indications that the outdoor temperature will have a strong impact on the CB operation. However, further investigations should be made in more extreme cold weather conditions. In such cases, the internal temperature of the mechanism should be measured when heaters are installed.

The software used for analyzing the vibration patterns has a configuration file where values for alarm and warning limits, the length of the vibration pattern to be included in the analyses, and the *elim* are set. The set values are based on initial vibration pattern recordings and analyses of the CB in question. The algorithm of the computer program itself is not altered.

## VI. CONCLUSION

Continuous vibration analysis seems to be a promising method for the mechanical diagnosis of important CBs. The first test installation identified a deviation in the CB condition that later caused the breaker to fail to open on command. The vibration pattern is little influenced by environmental conditions, and acoustic noise from the breaker arc is apparently not a problem. EM noise can, in some cases, be coupled to the instrument leads, and in such a case, a differential measurement setup is required. The recorded vibration patterns must contain several distinct events in order to be useful for diagnostic purposes. Reliability is important and special measures must be taken to prevent false alarms.

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