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IEEE Trial-Use Guide for the Detection of Acoustic Emissions from Partial Discharges in Oil-Immersed Power Transformers

Sponsor

Transformer Committee
of the
IEEE Power Engineering Society

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Abstract: This trial-use guide applies to the detection of partial discharges in power transformers. It takes advantage of the acoustic emissions produced by partial discharges. Although primarily intended for field use, it can also be used in the factory environment, if required.

Keywords: acoustic emission (AE), attenuation, burst, gas-in-oil analysis, low-amplitude discharges, partial discharge (PD), power transformers

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Introduction

(This introduction is not part of IEEE Std C57.127-2000, IEEE Trial-Use Guide for the Detection of Acoustic Emissions from Partial Discharges in Oil-Immersed Power Transformers.)

Publication of this trial-use guide for comment and criticism has been approved by the Institute of Electrical and Electronics Engineers. Trial-use guides are effective for 24 months from the date of publication. Comments for revision will be accepted for 18 months after publication. Suggestions for revision should be directed to the Secretary, IEEE-SA Standards Board, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, and should be received no later than 13 June 2002. It is expected that following the 24-month period, this trial-use guide, revised as necessary, shall be submitted to the IEEE-SA Standards Board for approval as a full-use guide.

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Contents

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IEEE Trial-Use Guide for the Detection of Acoustic Emissions from Partial Discharges in Oil-Immersed Power Transformers

1. Overview

1.1 Scope

This trial-use guide is applicable to the detection of partial discharges (PDs) in power transformers. It utilizes the acoustic emissions (AEs) produced by PDs. Although primarily intended for field use, this guide can also be used in the factory environment, if required.

IEEE Std C57.127-2000 is not intended to provide a precise method for defining the geometric location of the source of PDs, although it can sometimes provide a rough approximation of it.

1.2 Purpose

This trial-use guide organizes AE detection-measurement methods so that results may be compared by persons knowledgeable in this field, such as utility engineers, consultants, academics, and manufacturers.

1.3 Safety warnings

The safety warnings in this subclause and in 4.1 apply only to work done on transformers installed in the field, not to factory testing. **Refer to factory test codes for safety warnings for these situations.**

PD location should only be attempted by those technicians and engineers trained in working high-voltage transformers.

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WARNINGS

1) **The transformer tank must be connected to a low resistance ground to limit the extremely high voltages being induced into the ground circuit and the tank if a high voltage to ground failure occurs.** The personnel risk is very high if the transformer fails to ground. Even when grounded properly, the voltage on the tank to a different ground source may be **LETHAL** at the instant the failure occurs.
2) If the transformer is being energized or de-energized, or there is another type of power system voltage, **all personnel should maintain a reasonable distance from the transformer and equipment electrically connected to the tank due to the possibility of a failure.** It is recommended that acoustic measurement equipment connected to the tank be electrically isolated from the transformer tank, e.g., by optical means or by high-voltage electrical insulation, when measuring during transient events to eliminate the danger to the equipment or operators.
3) It is preferable to make all connections to the tank with the transformer de-energized, but in no case should the transformer voltage be above normal voltage while the sonic measuring devices are installed. **Personnel must not access areas where high voltages are within striking distance, such as on top of energized transformers or in bushing compartments**.
4) **The transformer ground circuit must never be changed (connected or disconnected) while the transformer is energized.** Even with the transformer de-energized, it is possible to have circulating currents in substation ground circuits; therefore, appropriate care should be exercised when connecting or disconnecting ground circuits.

2. Definitions

For the purposes of this trial-use guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B21][1] should be referenced for terms not defined in this clause.

2.1 acoustic couplant: A material introduced into the interface between the sensor and the transformer tank to facilitate the transfer of the mechanical signal from the steel wall to the sensing crystal. All liquids and many gels meet this criterion. Couplants produced for ultrasonic, nondestructive testing purposes are generally suitable; however, gelled glycerin or silicone grease are particularly efficient and are recommended.

2.2 acoustic emission (AE) burst rate: The number of groups of acoustic emission oscillations in a time interval, often 1 s, or a number of cycles, depending on the instrument being used. For example, there are nine bursts shown in the time interval, which is not defined, in Figure 1. The groups of acoustic emission oscillations are also called pulses.

2.3 acoustic emission (AE) oscillation: An oscillation produced by a resonant, piezo-electric crystal when perturbed by a shock wave, which could be caused by a partial discharge.

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[1] The numbers in brackets correspond to those of the bibliography in Annex A.

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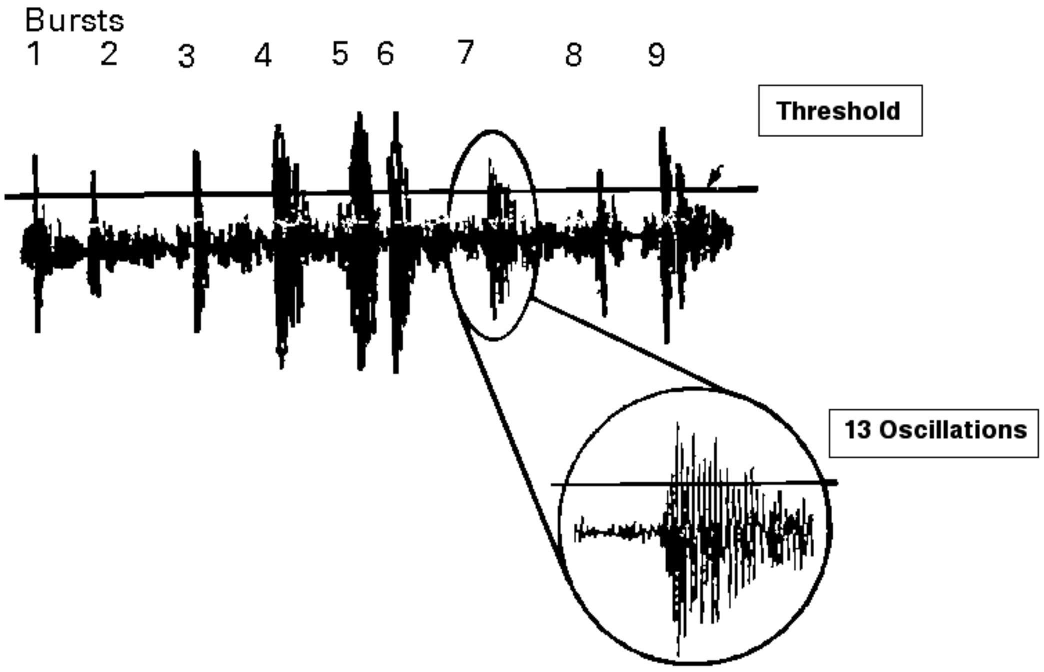

Figure 1—Typical AE oscillations

2.4 acoustic emission (AE) oscillation rate: The number of acoustic emission oscillations that exceed the counter threshold level in a time interval, often 1 s, or a number of cycles, depending on the instrument being used. For example, there are 13 oscillations in the detail of Figure 1. The time interval in the detail is not defined.

2.5 partial discharge (PD): An electrical discharge that only partially bridges the insulation between conductors.

2.6 partial discharge (PD) acoustic sensor or sensing transducer: A resonant, piezo-electric transducer that detects the mechanical stress waves that propagate from the partial discharge source through the internal construction materials and oil to the transformer tank wall. Note that the sensor is sensitive to stress waves in its frequency range that may not be from a partial discharge source.Instrumentation

3. Instrumentation

Many different types of instrumentation are available for detecting and displaying AEs. A typical system, which has been shown effective in certain transformer arrangements, is described in this trial-use guide. However, other detection systems may be equally or more effective, depending on the transformer physical parameters and the location of the PD. The main elements of the system are

- Sensing transducer
- Preamplifier
- Filter
- Power amplifier
- Counter
- Display
- Power supply

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3.1 Sensing transducer

The sensor is a piezo-electric displacement transducer operating in its compression mode and has a resonant frequency (for longitudinal waves) in the 120–160 kHz range. Because the sensor is a piezo-electric device, it will also respond to varying electromagnetic fields, such as those found in substations. To minimize this effect, the transducer can be either a "differential" type utilizing two crystals (mounted out of phase) or a shielded single crystal transducer with an integral preamplifier circuit. The latter is the preferred and most common configuration because its comparatively high-amplitude, low-impedance output is less susceptible to degradation due to noise pickup in the connecting cables.

The acoustic impedance of a sensing crystal differs from that of the steel transformer wall; therefore, for efficient transfer of the signal from the steel to the crystal, some users interpose a "matching piece." Although several materials may be used for this purpose, a hard-epoxy resin is convenient because it also provides some thermal and electrical isolation. However, care should be taken to select a resin that exhibits low acoustic attenuation (usually a function of the fillers used) so that it does not adversely affect the amplitude of the transmitted signal. Furthermore, as the acoustic impedance of epoxy resin does not numerically fall between that of steel and crystal, the thickness of the matching piece shall be equivalent to half the wavelength of the signal propagating in it—in this case, 150 kHz longitudinal waves.

The acoustic couplant gel or grease, defined in 2.1, is applied to the face of the transducer or matching piece just prior to the test.

3.2 Preamplifier

The preamplifier circuit can be either an integral part of the sensor package or a separate unit. The preferred configuration is the integral amplifier discussed in 3.1. In either case, the preamplifier circuit should accept high-impedance (approximately 10 000 Ω), low-amplitude (less than 100 μV) signals, provide a gain of about 40 dB, and be capable of working into a 50 Ω load. To preserve the integrity of the signal, the inherent noise produced by the preamplifier itself shall not exceed 3 μV referred to its input.

3.3 Filter

The filter is a band-pass type with lower and upper cutoff frequencies of F_L and F_H. These are frequencies at which the response to a constant sinusoidal input voltage has fallen by 3 dB from the maximum value. In this case, F_L should be about 100 kHz, and F_H should be about 300 kHz. The roll-off characteristics of the filter shall be a minimum of 48 dB/octave (240 dB/decade) for the high-pass section. This means that, relative to the signal of interest (150 kHz), a 50 kHz signal would be attenuated by 48 dB. The low-pass filter should roll off at not less than 24 dB/octave (120 dB/decade) so that a 600 kHz signal would be attenuated by 24 dB.

The purpose of the filter is to negate as many of the effects as possible of signals that are not associated with PDs. These include vibrations caused by the magnetostrictive action of the core (Barkhausen noise), pumps, and fans. Most of these fall below 30 kHz; however, the Barkhausen noise emanating from the core has been found to be in the 50 kHz range. Hence, a 100 kHz high-pass section with a rapid, roll-off response characteristic is needed. The reasonably generous band-pass (200 kHz) allows for variations between different transducers, in so far as their resonant frequencies are concerned.

Depending on location and source of the PD, some users find that a lower frequency (e.g., 60 kHz) is better, particularly when higher-frequency signals are attenuated. This type of sensor is more susceptible to external or other mechanical signals.

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3.4 Power amplifier

The power amplifier is to have a flat frequency response (± 5%) between 50 kHz and 300 kHz. Its gain must be adjustable in at least 2 dB increments over the range of 20–70 dB. The maximum inherent noise level produced by the amplifier should not exceed 100 µV referred to its input.

3.5 Counter

The counter circuit is to be capable of counting the number of individual oscillations contained in the AE signal during a time interval, commonly 1 s, or a set number of cycles. The amplitude threshold, in which this is to be carried out, should require a minimum signal-to-noise ratio of 3:1 for activation.

3.6 Display

The output from the counting circuit covers a wide dynamic range. Oscillation rates from 0 to 10^6 counts/s should be capable of being displayed. To accomplish this, a logarithmic or digital display is recommended. The physical display should be convenient and easy to read—bear in mind that it sometimes will be read in awkward locations in the field and often in bright sunlight.

3.7 Power supply

The detector is to be used on energized transformers; it should be powered by an isolated supply. This is necessary because the power-supply ground is unlikely to be the same physical ground as the transformer tank. Ground loops are to be avoided for both safety and noise reduction considerations. When size and transportation limitations do not preclude an adequate supply of power for the desired time period of monitoring, batteries may be used.

4. Test procedure

4.1 Introduction

The instrumentation and techniques described in this trial-use guide are intended for the detection of the low-amplitude mechanical stress waves that are produced by PDs taking place within transformers. Consequently, the test can only be carried out on energized equipment, and adequate safeguards must be involved.

WARNING

The following test procedure requires that the operator make contact with the apparatus being evaluated. **It is mandatory that such contacts involve only adequately grounded surfaces.** Bushings and other electrical components are not necessarily adequately grounded. Therefore, the evaluation of such components (bushings, etc.) by means of this test procedure is not recommended, and is **HAZARDOUS.**

The technique and test procedure described are intended for exclusive use on oil-filled equipment with adequately grounded metal walls. **Use in any other environment could be DANGEROUS.**

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4.2 Background

Each PD occurring within the insulation produces a low-amplitude mechanical pulse, which propagates to the tank wall where it can be detected by an appropriate sensor. The output of the sensor will be proportional to the energy content of the forcing function (pulse). Because the sensor contains a resonant crystal, it will oscillate at its natural frequency. The amplitude of these oscillations will then decay exponentially due to the mechanical damping inherent in the crystal. Consequently, each pulse arriving at the transformer tank wall will result in a "burst" type signal from the transducer. One burst is produced for each PD detected.

The number of oscillations contained within each burst is determined by the amplitude of the forcing function (pulse from the PD) that excited the crystal. An accounting of the number of these oscillations, which occurs within a 1 s interval, or a set number of cycles, contains information relative to both the number of discharges that occurred within that time interval as well as their amplitude.

The amplitude of the mechanical pulse is attenuated as it propagates through the insulation and oil during its journey to the tank wall. Consequently, the oscillation count rate will be at its maximum when the sensor is at its closest proximity to the source. This effect enables the operator not only to detect the presence of PDs, but also to estimate the approximate location of their source.

4.3 Instrument adjustment

The sensor is to be connected to the instrument by means of an appropriate shielded cable. If the preamplifier is included in the transducer package (the preferred arrangement), the cable should be a 50 Ω characteristic-impedance shielded coaxial cable not more than 30 m long. If the preamplifier is a separate unit, it should first be connected to the sensor with a high-impedance shielded coaxial cable not exceeding 1 m in length.

Subsequent connection between the preamplifier and power amplifier should then be made with a 50 Ω characteristic-impedance coaxial cable no longer than 30 m long.

With the transducer connected and suspended in such a manner that it does not come in contact with any object, the power amplifier gain should be increased to a point where its own noise causes random pulses to be detected when the counting threshold is set to 1 V. With the amplifier set at this level, the counter threshold level should then be raised to 3 V, thus requiring a signal-to-noise ratio of 3:1 for actuation of the counter circuit during testing operations.

4.4 Test procedure

This test procedure is suitable for the attended inspection of transformers only. Its use for unattended long-term monitoring is not recommended due to the confusing signals produced, for example, by rain.

AE signals produced by PDs propagate through the oil to reach the transformer tank wall. Therefore, all attempts to detect such AEs should be carried out below the top oil level.

As previously stated in 4.1, this technique is designed for use on metal transformer tanks that are at ground potential. The following procedures, therefore, apply only to that mode of operation.

a) The instrument should be set up as previously described in 4.3, with care being taken to ensure that the power source selected is adequate for the type and length of tests planned.

b) Sufficient couplant is to be applied to the face of the transducer to ensure efficient transmission of the AE signal from the tank wall to the sensing crystal. Ideally, the face of the transducer should be covered with a film of couplant approximately 0.5 mm thick. The use of more couplant will not be

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harmful (though wasteful), whereas too little couplant can seriously inhibit the transducer's sensing capabilities.

c) The face of the transducer with its film of couplant should be brought into contact with the transformer tank wall with only sufficient pressure applied in order to hold it in position. It is only necessary to hold the sensor steady so that no signals are generated due to relative movement between the sensor and tank wall. This can be achieved either by means of a magnetic clamp or adhesive tape. However, with care and a little practice, the sensor can be quite successfully hand held.

d) If PD activity is detected at any location, the foregoing procedure should be repeated at other positions on the transformer in order to locate the position where a maximum oscillation count rate is obtained. This is the position on the tank wall where the sensor is closest to the PD source. The oscillation count rate obtained at that location also provides the best estimate of the activity level of the emitting PD source. There will be more than one area where maximums are observed if there are multiple PD sources.

e) The functioning of the transducer and instruments can be tested by tapping on the face of the transducer or by placing the face of the transducer against the tank wall and breaking the lead of a *#2* pencil on the tank wall next to the transducer.

5. Interpretation of results

This clause is included as a guide to the types of signals that may be encountered. It is not intended as a definitive description of all types of faults and their signatures.

5.1 Amplitude of individual discharges

The oscillation count rate is related to the total amount of PD activity detected during a short time interval. However, it gives little indication of the amplitude of the individual discharges that have occurred. (For example, the same oscillation count rate could be obtained from many discharges of low amplitude as could be obtained from a few discharges of high amplitude.)

This situation can be resolved by also taking into account the burst count rate. A high oscillation count rate, coupled with a high burst count rate is indicative of many low-amplitude discharges. On the other hand, a high oscillation count rate coupled with a low burst count rate is indicative of fewer, high-amplitude discharges.

5.2 Effect of attenuation

The construction materials (pressboard, solid insulation, conductor materials, etc.) all attenuate the mechanical stress wave as it propagates to the tank wall. The situation is further complicated by the fact that each of these materials exhibits different attenuation characteristics. For this reason, it is not possible to quantify the discharge level through the oscillation or burst count rates. To achieve this, it would be necessary to know the exact location of the PD source and details of the materials in the propagation path of the pulses. It may then be possible to calculate the amount of attenuation present and apply the necessary compensation (increase) to the observed oscillation count rate. As this is rarely a practical approach in the field, the observed pulse rate should be taken as indicative of the minimum level of activity that is present, since compensation for attenuation would always result in a higher estimate.

5.3 Characterization of signals

In general, two types of result (other than zero) may be encountered. One in which “continuous” readings are obtained, while the other produces “sporadic” readings. By *continuous* it is meant that activity is present all the time, though not necessarily producing a nonvarying oscillation count rate—count rates may vary but never decline to zero. This type of signal is typical of that produced by an energetic PD source. Usually, this sensor is associated with reasonably high count rates and a well-defined location.

“Sporadic” activity can be further subdivided into two types. One in which the activity is present most of the time, but short quiescent periods are also encountered. This type of signal is usually produced by exposed sources on conductors, connectors, and worn tap changers. The second type of “sporadic” signal is typified by lengthy quiescent periods (perhaps minutes) followed by short periods of very high activity. This type of signal usually has been found to be associated with floating static shields. Often short-lived arcs are associated with this type of fault, and these produce very energetic AE signals during active periods.

As previously described, it is often possible to determine the position on the tank wall where the transducer is closest to the PD source. This, however, gives no information as to the distance into the tank (from that location) to the source. However, observing the signal on an oscilloscope (a digital transient recorder is recommended), it is possible to form an opinion regarding this. For example, the pulse shown in Figure 1 has suffered very little attenuation. This is evidenced by the high rise rate of the leading edge of the burst envelope, resulting in the characteristic “arrowhead” shape. To achieve this, the propagation path is almost entirely in oil with little solid insulation involved. If the same signal had propagated through layers of insulating materials, the resulting attenuation would not only have affected the overall amplitude, but also modified the burst envelope by “rounding off” the leading edge. In the extreme, the burst envelope becomes “egg shaped” as shown in Figure 2. By utilizing this phenomenon, it is possible to estimate whether the source lies close to the surface or is buried well within the insulation system.

The foregoing involves the use of ancillary instrumentation not normally available in the field. It is, therefore, most often applied in the field if circumstances warrant the added complication.

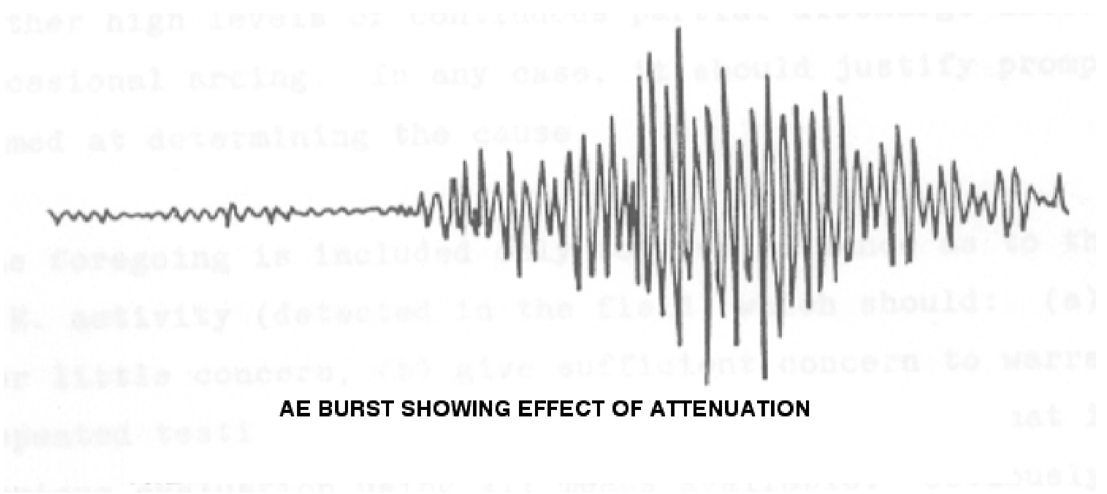

Figure 2—Typical AE burst

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5.4 PD activity levels

In the laboratory it is possible to calibrate the AE oscillation count rate with electrical PD levels (in picocoulombs); however, this correlation should not be used in the field due to the effects of attenuation in both the acoustic and electrical signals. This means that no absolute value of PD activity can be determined from AE measurements made in the field.

It is important to verify whether the acoustic signal is due to internal PDs or if it is due to mechanical noise. To make this determination requires the expertise of the investigator, and other evidences such as the presence of indicating combustible gasses or electrical PD.

In general it is true that a more intense PD source will produce a higher count rate than a weak source. This is because, at the site of an intense discharge, there are multiple locations or perturbations that are each producing PDs and AEs. However, it is necessary to recognize the differences in making acoustic measurements on large power transformers vs. smaller ones.

a) **Large power transformers:** The locations of the PDs that are likely to lead to failure in large power transformers may be in areas where the attenuation of the PD signal is great. These would include areas within the windings and in the high-low spaces. In this instance, a source that is likely to lead to failure will be attenuated to the point that the AE count rate is low.

   With large power transformers, there are generally more attenuation sources due to the thicker tank walls, the presence of more insulation barriers, forced oil-air (FOA) wraps, tank wall shielding, etc. Because the value of the large power transformer is so high and the cost of a catastrophic failure is so great, the detection of any internal PDs in large power transformers should be a cause for further investigation. This might include close monitoring of the behavior of the discharge with time, more frequent samples of oil for combustible gas measurements, and other advanced diagnostic measurements.

b) **Smaller core form transformers that do not have tank wall shielding and/or FOA barriers whose tank wall thickness is 1/4 in or less:** A given PD will probably produce more acoustic energy at the transducer location than a larger transformer with 3/8 in tank wall thickness and tank wall shielding.

   Because of this, there may be more justification for taking a less conservative approach such as characterizing the PD count rate—a detected oscillation count rate of 10 000 counts/s should be cause for further investigation. The level of activity necessary to produce oscillation count rates in the range of 100 000 counts/s should be cause for considerable concern. Typically, this type of result requires the existence of either high levels of continuous PD activity or occasional arcing. In any case, it should justify prompt actions aimed at determining the cause.

   The foregoing is included only to give guidance as to the level of AE activity detected in the field that should

   1) Give cause for little concern
   2) Give sufficient concern to warrant further repeated testing
   3) Be of sufficient concern that it prompts serious evaluation using all means available

   Obviously, the data obtained from this type of test is not sufficiently definitive to warrant its use as either acceptance or go/no-go criteria, and should not be used as such.

   It can be seen that by taking into account the type of signal obtained, the approximate location of the emitting source, and an estimate of the level of the activity involved, it is reasonable to use the acoustic measurement as a means of identifying potential PD problems. While the acoustic measurement alone may not provide an estimate of the severity of the problem or the assessment of its cause, it can indicate the need for other diagnostic measures, which when combined with the acoustic data, will often provide the means for identifying the cause and severity of the problem.

5.5 Integrating AE results with data from oil analysis

Although AE data is useful in its own right, it becomes even more useful when used in conjunction with other information, such as dissolved gas-in-oil data. Assuming that the problem has been present for some time, as is typical of situations that develop in the field, good correlation should be expected between gas analysis and AE data. If a gas analysis shows the existence of constituents associated with the degradation of cellulose due to PD activity and the AE data indicates a continuously emitting source in the area of one of the coils, there is a good possibility that a PD is present in the area indicated. (Refer to IEEE Std C57.104-1991 [B22].)

The two sources of data can often supplement each other in yet other ways. For instance, sometimes the breakdown of constituents in the gas analysis is so complex that, although it is obvious that a significant problem is involved, it is not possible to determine whether the cause is due to PDs or is thermal in origin. The AE system responds only to signals produced by PDs or arcs. Purely thermal phenomena do not produce such signals. Therefore, the existence of any AE signal together with the complex gas analysis may confirm the existence of PDs. Conversely, the absence of AE activity in this case may indicate that the problem is basically thermal in origin. As the combination of information produced by these two techniques is so advantageous, it is particularly recommended that gas analysis results be taken into account when interpreting AE data.

The foregoing comments are particularly aimed at the evaluation of units in the field. When evaluating transformers on the shop floor, the same good correlation between dissolved gas and AE data is not usually obtained. AE technique provides essentially real-time data relative to activity occurring at that instant. Oil analysis, on the other hand, is to some extent historical in nature. It is necessary for a PD to be active for some time before sufficient gas is generated so that it is detectable in the large volume of oil present. When the unit is new, or the insulating fluid is new or reprocessed, it is unlikely that PD-related faults would be present for a long enough period of time to be reliably detected by gas analysis. Normally, radio-influence voltage (RIV) or “apparent charge” detection is carried out in the factory, and this provides an alternate database for correlation with AE data in the signal interpretation process.

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Annex A

(informative)

Bibliography

Since the early 1950s, there has been much activity in the area of ultrasonic/acoustic emission detection of PDs. Consequently, the amount of literature now available is too large to allow for complete documentation. The following bibliography is intended to give a broad overview of the subject and provide references for further study.

[B1] Anderson, J. G., "Ultrasonic Detection and Location in Insulating Structures," *AIEE Transactions,* no. 75, 1956.

[B2] Application Note AN23, "Table of Ultrasonic Properties." Metrotek Inc., Richland, WA, 1982.

[B3] Bartnikas R., and McMahon, E. J., "Engineering Dielectrics," *Corona Measurement and Interpretation,* vol. 1, chapter 10, edited by R. T. Harrold, ASTM Publication, STP669, 1979.

[B4] Bengtsson, T., and Jönsson, B., "Transformer PD Diagnosis using Acoustic Emission Technique," *ISH-97*, no. 115.

[B5] Bengtsson, T., Leijon, M., and Ming, L., "Acoustic Frequencies Emitted by Partial Discharges in Oil," ISH-93, no. 63.10.

[B6] Berent, D., *Acoustic Monitoring and Gas-In-Oil Analysis for Transformers*, Doble Engineering Company, Report #62PAIC95, pp. 831–836.

[B7] Boguslaw, J., "Utilization of Acoustic Emission for Detection, Measurement, and Location of Partial Discharges," *AEWG-Second International Conference on Acoustic Emission,* Lake Tahoe, NV, 1985.

[B8] Carpenter, J. H., Kresge, J. S., and Musick, C. B., "Ultrasonic Corona Detection," *IEEE Transactions,* PAS-86, no. 8, 1965.

[B9] Edmonds, Peter D., "Methods of Experimental Physics," *Ultrasonics,* vol. 19, pp. 18–19, New York: Academic Press, 1981.

[B10] Eleftherion, P. M., "Partial Discharge XXI: Acoustic Emission-Based PD Source Location in Transformers," *Proceedings IEEE Electrical Insulation Magazine,* 08837554/95, 1995.

[B11] EPRI EL-4009-1985, Acoustic Emission Detection of Partial Discharges in Power Transformers.

[B12] Fredrick, J. R., *Ultrasonic Engineering*. New York: John Wiley & Sons, pp. 13–21, 1965.

[B13] Harrold, R. T., "Acoustical Properties of Insulating Liquids and Gases," *IEEE International Symposium of Electrical Insulation,* Philadelphia, 1978.

[B14] Harrold, R., "Acoustic Waveguides for Sensing and Locating Electrical Discharges in High Voltage Power Transformers and Other Apparatus," *IEEE Transactions On Power Apparatus and Systems,* vol. PAS-98, no. 2, pp. 449–457, Apr. 1979.

Copyright © 2000 IEEE. All rights reserved.

[B15] Harrold, R. T., “The Relationship Between Ultrasonic and Electrical Measurements of Under Oil Corona Sources,” *IEEE Transactions on Electric Insulations,* vol. EI-11, pp. 8–11, Mar. 1976.

[B16] Heroux, P., “A Statistical Study of Electrical and Acoustical Characteristics of Pulsative Corona,” TGIAO, *IEEE paper AT6 122–2,* Winter Power Meeting, 1976.

[B17] Herzfeld, K. F., and Litovitz, T. A., *Absorption and Dispersion of Ultrasonic Waves*. New York: Academic Press, p. 454, 1959.

[B18] Howells, E., “Acoustic Emission from Stressed Dielectric Liquids,” *ISA paper no. 74219 Instrumentation Symposium*, Albuquerque, 1974.

[B19] Howells, E., and Norton, E. T., “Detection of Partial Discharges in Transformers Using Acoustic Emission Techniques,” *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-97, no. 5, 1978.

[B20] Howells, E., and Norton, E. T., “Parameters Affecting the Velocity of Sound in Transformer Oil,” *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-103, pp. 1111–1115, May 1984.

[B21] IEEE 100, The Authoritative Dictionary of IEEE Standards Terms.[2]

[B22] IEEE Std C57.104-1991, IEEE Guide for the Interpretation of Gasses Generated in Oil-Immersed Transformers.

[B23] IEEE Std C57.113-1991, IEEE Guide for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors.

[B24] Kawanda, H., Honda, M., Inoe, T., and Amemya, T., “Partial Discharge Automatic Monitor for Oil-Filled Power Transformers,” *IEEE paper no. 833M424–8,* PES Summer Meeting, 1983.

[B25] Krautkramer, J., *Ultrasonic Testing of Materials*. New York: Springer-Verlag Inc., 1969, pp. 20–23.

[B26] Morel, J. F., and Fallow, B., “Detection and Location of Partial Discharges by Ultrasonics,” *ERA Transactions 2947,* Rev. General Electric, vol. 80, pp. 225–228, 1971.

[B27] Noro, A., Nakamura, K., Horii, K., Katsukawa H., and Matsuoka, R., “Acoustic-Based Real-Time Fault Location in Power Substation,” *Third International Symposium on Electricity Distribution and Energy Management, Proceedings,* pp. 106–111. 1993.

[B28] Noro, A., Nakamura, K., Watanabe T., and Morita, T., “Acoustic-Based Real-Time Partial Discharge Location in Model Transformer,” *Proceedings ICSPAT ’94,* pp. 1077–1082.

[B29] *Partial Discharge Detection Using Acoustic Emission*. Princeton: Physical Acoustics Corporation.

[B30] Reason, J., “Online Transformer Monitoring,” *Electrical World,* Special Report, pp. 19–26, Oct. 1995.

[B31] Shertukde, H. M., Alnajjar, H., and Prabhune, U., “Fault Detection Device For Electrical Power Transformers Using Novel DSP Scheme,” *Proceedings ICPAT'96,* Boston, MA, pp. 1219–1223, Oct. 7–10, 1996.

[B32] Shertukde, H. M., and Bar-Shalom, Y., “Target Parameter Estimation in the Near Field with Two Sensors,” *IEEE Transactions on Acoustic Speech and Signal Processing,* vol. 36, pp. 1357–1360, Aug. 1988.

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[2] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

Copyright © 2000 IEEE. All rights reserved.

[B33] Shertukde, R. H., and Shertukde, H. M. "Manufacture of Fault Diagnostic Device for Electrical Power Transformers (FD2EPT)," *Proceedings ICSPAT'96,* Boston, MA, pp. 1229–1233, Oct. 7–10, 1996.

[B34] Titto, S., Olata, M., and Saynajakangas, S., "Non-Destructive Magnetic Measurements of Steel Grain Size," *Non-Destructive Testing Journal,* England, 1976.

[B35] Train, D., Mercier, A., and Thorne, D., "The Detection of Partial Discharges in High Voltage Potential Transformers in Service," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-93, pp. 1909–1916, Nov. 1974.

[B36] Vohl, P. E., Gervais, Y., and Mukhedkar, D., "Model Analysis of Pulses Generated by Partial Discharges," *IEEE paper no. A76-4168,* PES Summer Meeting, 1976.

[B37] Wood, J. W., Hickling, G. H., Hindmarch, R. T., and Raju, B. P., "Electrical and Ultrasonic Characteristics of Partial Discharges in Oil Immersed Insulation," *IEEE Conference on Dielectric Materials, Measurements and Applications,* Cambridge, England, 1975.

[B38] Young, R. K., *Wavelet Theory and Its Applications*. Boston: Kluwer Academic Publishers, 1994.

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Annex B

(informative)

Instrumentation calibration

B.1 Introduction

The circuitry in the instrument external to the sensor is required to perform the following functions:

a) Provide 60 dB of gain to the incoming signal
b) Severely attenuate signals outside the frequency range of 100–300 kHz
c) Produce a 3:1 signal-to-noise ratio for actuation of the pulse counting process

The procedure in B.3 is designed to verify satisfactory operation.

B.2 Equipment required

The following equipment is required:

a) Signal generator (with low-output voltage capability)
b) Frequency counter
c) Precision voltmeter with high-frequency (500 kHz) response capability and preferably peak voltage indication

B.3 Procedure

Connect the signal generator to the input of the PD detector. Connect the voltmeter across this input so that it monitors the voltage level of the applied signal. Connect the counter to the output of the signal generator to monitor the frequency of its output.

a) Adjust the signal generator to supply a 150 kHz sinusoidal signal with peak amplitude of 1 mV.
b) Set the power amplifier gain to 60 dB ± 1 dB.
c) Set the pulse counter circuitry trigger level to 1 V. The instrument display should indicate an oscillation count rate of 150 000 pulses/s.
d) Raise the instrument counter trigger level to 3.00 V. The counter should now indicate 0.
e) Slowly increase the amplitude of the applied signal (still at 150 kHz), noting the voltage necessary to activate the counter circuit and result in a 150 000 pulses/s display. This amplitude should be no less than 3.00 mV and no more than 3.20 mV.
f) With the system setup as previously described (3.00 V counting level; 60 dB power amplifier gain; and 3 mV, 150 kHz input), reduce the frequency of the input signal to 100 kHz. The counter should now indicate 0.
g) With the same setup, increase the frequency of the input signal to 300 kHz. The counter should again indicate 0.

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h) Without changing the instrumentation configuration, slowly vary the input signal (at constant 3 mV peak amplitude) over the range of 100–300 kHz. Correct indication should only be obtained when the frequency of the input signal is between 120 kHz and 280 kHz.

Completion of these checks ensures satisfactory performance of the power amplifier, filter, and signal-to-noise ratio discriminator and counter circuits.

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Annex C

(informative)

Calibration of transducer and preamplifier

C.1 Introduction

The sensor utilizes a piezo-electric crystal with a nominal resonant frequency of 150 kHz when excited by a longitudinal waveform. The output from the crystal is a very low-amplitude, high-impedance signal that requires processing in a preamplifier before it is useful. The transducer element and preamplifier is to be considered as a complete system, whether they are contained in the same package (as in the preferred shielded single crystal sensor) or as separate units.

C.2 Instrumentation required

a) Heavily damped, 5 mHz, ultrasonic, non-destructive testing immersion transducer.

b) Transducer excitation pulse circuit—This is required to provide a positive going pulse, achieving a peak amplitude of 300 V in 500 ns, and decaying to 0 amplitude in 3 µs. The circuit is required to work into a high-impedance load and have a pulse repetition rate of approximately 1 kHz.

c) Transient recorder—A digital oscilloscope with a 500 ns sampling rate is recommended.

d) Spectrum analyzer—This should be capable of analyzing transients and processing signals with a frequency content up to at least 300 kHz.

e) Ultrasonic immersion test tank.

f) Appropriate preamplifier power supply.

C.3 Procedure

The intent of this procedure is to determine the output of the PD sensor/preamplifier combination to a well-defined longitudinal mechanical pulse. To achieve this, the pulsing circuit excites the ultrasonic (driving) transducer so that it outputs a well-defined mechanical pulse. Having been submerged in water, this pulse propagates exclusively in the longitudinal mode and subsequently excites the sensor being evaluated. The output of the sensor/preamplifier combination is then supplied to a transient recorder where the time-domain record is obtained. At the same time, the signal is supplied to a spectrum analyzer for frequency analysis.

a) Connect pulser circuit to ultrasonic (transmitting) transducer.

b) Connect appropriate power supply to sensor/preamplifier combination.

c) Connect sensor/preamplifier output to transient recorder and in parallel to the spectrum analyzer.

d) Set transient recorder sampling period to approximately 500 ns and transient capture trigger level to approximately 2 V.

e) Set spectrum analyzer in the transient analysis mode and select a frequency range that embraces at least 0–250 kHz.

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f) Immerse both driving transducer and discharge detector sensor in the water-filled immersion tank. Ensure that they face each other squarely and are 16–17 cm apart. The transducers should be located at least 8 cm away from any reflecting objects such as the tank walls. It is also important to ensure that no bubbles adhere to the face of either the transmitting transducer or sensor.

g) Energize transducer excitation pulse circuit and preamplifier power supply.

The time-domain signal displayed by the transient recorder should be that of a “burst” made up of many oscillations. The leading oscillations should be high in amplitude with the remainder decaying to zero, similar to that shown in Figure 1. The requirements are that the maximum peak-to-peak voltage be no less than 5.80 V and no higher than 6.20 V. The duration of the burst should be no less than 80 µs and no longer than 150 µs.

To avoid the confusing effects of random noise, it is recommended that the spectrum be enhanced by averaging at least eight separate spectra. The resulting spectrum should show a dominant peak between 120 kHz and 160 kHz. The resonant characteristic of the crystal should be evident by the amplitude of this peak being at least 40 dB and no more than 43 dB above the spectrum reference level.

In meeting these criteria, the sensor is shown to have a lightly damped crystal of the correct resonant frequency and the preamplifier is producing the required 40 dB of gain.

Note—The foregoing procedure requires that the PD detection sensor be completely immersed in water. If a sensor that is not suitable for total immersion is used, the same result can be obtained by utilizing a vertical water column. In this case, the driving transducer is located about 8 cm from the bottom of the column, while only the face of the sensing transducer is required to enter the water surface. If this approach is used, the same precautions relative to reflections from the tank sides, avoidance of bubbles, and separation distance between the sensors are still appropriate.

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