



IEEE Guide for the Detection and Location of Acoustic Emissions from Partial Discharges in Oil-Immersed Power Transformers and Reactors

IEEE Power Engineering Society

Sponsored by the
Transformers Committee

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**Transformers Committee
of the
IEEE Power Engineering Society**

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Abstract: The detection and location of acoustic emissions from partial discharges and other sources in oil immersed power transformers and reactors are covered in this guide. A means of associating the relative magnitude and position of partial discharges and other sources with the acoustic signals obtained by strategically located transducers is provided.

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

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Introduction

This introduction is not part of IEEE Std C57.127-2007, IEEE Guide for the Detection and Location of Acoustic Emissions from Partial Discharges in Oil-Immersed Power Transformers and Reactors.

The guide is an expansion of IEEE Std C57.127™-2000. It has been expanded to include more theory and signal interpretation information, newer techniques for detection, and the concepts for location. Active workers in the field are constantly trying to improve their methods. More effective methods may appear in the future.

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1. Overview

1.1 Scope

This guide is applicable to the detection and location of acoustic emissions from partial discharges and other sources in oil immersed power transformers and reactors. Both electrical sources (partial discharge) and mechanical sources (such as loose clamping, bolts, or insulation parts) generate these emissions. There are descriptions of acoustic instrumentation, test procedures, and interpretation of results. When this guide is used with oil-immersed reactors, it must be understood that interpretation of signals may be different because of the construction of the reactor.

Accuracy of location depends on the type of fault, configuration of tank, type of instrumentation, and experience.

1.2 Purpose

This guide is intended to provide information that may be helpful in planning, installing, and operating acoustic monitoring equipment and in meaningful interpretation of resulting data. Users are intended to be persons knowledgeable in this field such as utility engineers, consultants, academics, and manufacturers.

1.3 Safety warnings

The safety warnings in this subclause 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.

Partial discharge (PD) location should only be attempted by those technicians and engineers trained in working on high-voltage transformers and knowledgeable of the risks associated with this work.

WARNING

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.

WARNING

If the transformer is being energized or deenergized, 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.

WARNING

It is preferable to make all connections to the tank with the transformer deenergized, 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 minimum approach distance, such as on top of energized transformers or in bushing compartments.

WARNING

The transformer ground circuit must never be changed (connected or disconnected) while the transformer is energized. Even with the transformer deenergized, 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 guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B33]¹ may be referenced for terms not defined in this clause.

2.1 acoustic couplant: A material used at the structure-to-sensor interface to improve the transmission of acoustic energy across the interface during acoustic emission monitoring.

NOTE—See 6.5.²

2.2 acoustic emission (AE): The phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material, or the transient waves so generated.

NOTE—See 5.1.

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

² Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

2.3 acoustic impedance: The decisive factor for determining reflection and transmission properties when passing from one acoustic medium to another. The acoustic impedance is denoted Z and defined as density (γ) times the propagation velocity (v), $Z = \gamma v$.

2.4 AE burst: A group of AE oscillations constituting a transient signal.

NOTE: See 5.1.

2.5 AE burst rate: A rate that denotes the actual number of discrete AE events or bursts per unit time, usually 1 s, or per cycle of the ac voltage wave.

2.6 AE oscillation: An oscillation produced by a resonant piezoelectric crystal when perturbed by a shock wave, which could be caused by a partial discharge.

2.7 AE oscillation rate or count rate: The number of AE 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.

NOTE—See 5.1.

2.8 Barkhausen effect and magnetostriction noise: Noise associated with the deformation of magnetic domains in the core of a transformer.

NOTE—See item a) of 10.8.

2.9 critical angle: The largest incidence angle (from normal) for which a wave can enter a medium that has a higher propagation velocity.

2.10 direct acoustic (oil-borne) path: Path of propagation from the PD acoustic signal source directly (straight line) to the sensor location on the tank wall, without obstruction such as windings, core, or major blocking/bracing.

2.11 pressure wave (also called longitudinal wave): A wave that consists of alternate compression and rarefaction forces in the direction of propagation. It occurs in both liquids and solids.

2.12 shear wave (also called transverse wave): A shock wave in the oil impinging at normal incidence on the tank will generate motion in the tank wall that is perpendicular to the propagation direction similar to a vibrating string. A shear wave requires an acoustically solid material for effective propagation and therefore does not exist in the oil; it exists only in the steel.

2.13 speed of sound in steel: The velocity of various waves in steel follow: longitudinal wave about 5900 m/s; extensional wave about 5200 m/s; transverse wave about 3200 m/s.

2.14 structure-borne path: Propagation of the PD acoustic signal through the transformer structure.

3. Detection and measurement of PD—Background information

Since PD cannot be measured directly, its energy by-products such as electrical transients, chemical changes, electromagnetic emissions, vibration, sound, light, and heat must be measured. Each of these energy by-products, when measured, has advantages and disadvantages for identifying PD. The measurement methods are as follows:

- a) Radio frequency—VHF: The VHF measurement of radio waves is in the frequency range of 30 MHz to 300 MHz. This VHF measurement is usually associated with aerial antennas, but not exclusively. Some window-type receiver devices may also monitor the VHF range. The signal attenuation and noise reduction are similar but less compared to the UHF frequency.

- b) Radio frequency—UHF: The UHF measurement of radio waves is in the frequency range of 300 MHz to 3 GHz. These measurements are often performed using a window style UHF receiver. UHF tests are less affected by external noise. The corona type of PD emits only up to a frequency of approximately 300 MHz. Signals are strongly attenuated when they pass through the bushings or travel longer distances within the oil. Cell phone and TV stations operate in the UHF band and might introduce strong noise. Discharges directly in the oil have an upper frequency limit of only a few hundred kilohertz and cannot be detected.
- c) Radio-frequency current transformers (RFCT): RFCTs are designed to measure up to several tens or hundreds of megahertz. They can be placed on ground returns and/or bushing taps. The RFCT by itself is generally considered non-intrusive; however, the RFCT may require an outage to be installed. It can be used both for off-line and on-line measurement states.
- d) Coupling capacitor (CC): The CC sensor interfaces directly with the voltage terminal. This is the method described in IEC 60270 [B36]. This is a common factory test method. Results are measured in picocoulombs. This measurement works well under a controlled noise-free environment, but may not work well in a field environment.

For field measurements, this method can utilize either a user-supplied capacitor or the leakage current from a bushing tap, using the condenser layered bushing as the coupling capacitor. When the user supplies an external reference capacitor for on-line measurements, the measurement is considered intrusive. However, when a coupling capacitor is used, there is generally no limitation put on the frequency measurement range.

- e) Acoustic emission (AE): Consists of one or more ultrasonic transducers that are sensitive to the AE generated by a PD source. Acoustic sound sources are wide-banded (> 1 MHz). Due to the propagation characteristics of the insulation medium and apparatus structure, ultrasonic AE is measured in the 20 kHz to 500 kHz frequency range.
- f) Ultraviolet (UV) light: Detects UV light generated by corona, external PD on surfaces, and arcing. This method generally detects external events within line-of-sight. With the help of daylight blocking filter and very sensitive cameras, UV measurements can be obtained in direct sunlight.
- g) Dissolved gas analysis (DGA): In the case of PD in voids or gas bubbles, the main gas formed is hydrogen together with significant amounts of methane (typically 10%) and minor amounts of the other gases. Variable amounts of the carbon oxides may also result from partial discharges in cellulose, although usually in lower quantities than the other gases [B16], [B17].

In the case of discharges of the sparking-type in oil or in paper, significant amounts of all the hydrocarbons (including acetylene) are formed in addition to hydrogen.
- h) Power factor tip-up: PD produces a power loss, which is a function of applied voltage. If PD is present, losses increase and the power factor changes with applied voltage. The power factor difference between applied voltage levels is known as “tip-up.”

This guide focuses on the detection and location of PD using AE techniques. These techniques are sometimes combined with one or more of the previously listed PD detection and measurement methods.

4. Introduction to acoustic PD systems

PD detection and location work is carried out in the factory and in the field, the latter being done with the transformer either connected to the grid or supplied by a separate power source.

Acoustic PD systems are most often used when PD has been identified as a result of other diagnostic procedures, such as dissolved gas analysis and electrical PD measurement.

There are two general categories of acoustic location systems: all-acoustic systems and acoustic systems with an electrical PD trigger. In addition, on-line (continuous) acoustic monitoring systems are being used primarily to detect and trend emissions. Typical implementations of each of these types of systems are given in 4.1, 4.2, and 4.3 along with the respective advantages and limitations.

4.1 All-acoustic system

The first category, the all-acoustic system, consists of one or more ultrasonic transducers that are sensitive to the AE generated by a PD event. The detection and coarse location of one or more sources can be accomplished by moving one or more externally mounted sensors to different locations on the transformer tank. A more precise location of a PD source may be determined by the relative arrival times of the acoustic signals at each of the sensors. No voltage or current readings are required on the transformer. This makes the all-acoustic system a suitable tool for source location on operating transformers in the field.

The acoustic transducers can be mounted on the exterior of the transformer tank to detect the acoustic signal as it hits the tank wall, or inside the transformer to detect the signal in the oil.

Benefits of the externally mounted sensors include the ability to reconfigure the sensors as necessary to obtain a clearer acoustic signal, the flexibility to move the system to another transformer, and the ease of retrofitting existing transformers. The disadvantage of the external configuration is that it is more sensitive to external noise sources.

Benefits of the internally mounted sensors may include a clearer, louder measurement with a better signal-to-noise ratio. Disadvantages are that installation of the sensors is invasive to the transformer and, once installed, the sensors can not be moved around to achieve a clearer line-of-sight to the source, nor can they be easily removed and installed on another transformer.

4.2 Acoustic system with an electrical PD trigger

The second category, the acoustic system with an electrical PD trigger, pairs the array of acoustic sensors described in 4.1 with a current or voltage measurement device that detects the PD signal electrically. The electric signal is usually considered as detected instantaneously. When using this assumption, the arrival time of the electric signal is used as time zero for the PD event. The difference in arrival times of the electric signal and an acoustic signal is the propagation time between the PD source and that sensor location. PD location is based on the absolute arrival time at each sensor, as opposed to the all-acoustic system described in 4.1 that uses the difference in arrival time between sensors.

The assumption of instantaneous detection of the electric signal is correct when it appears, e.g., at the bushing tap of the transformer. At the most, this delay is in the range of a few microseconds and therefore can be neglected. However, an acoustic system with an electrical PD trigger is processing the electrical signal first. Here the processing time may be taken into account in order to decrease location error. Table 1 shows the time lags due to the analog processing time measured in three different electrical PD detector types.

The numbers are provided only as an example. Other detectors from different manufacturers may have different time lags since this property is not specified in the standards. It can be seen that a narrowband detector may introduce a time lag that may be taken into account if very accurate location measurements are desired.

One advantage of the combined system is that the electrical measurement provides confirmation that the acoustic sensors are locating a PD event as opposed to another acoustic noise source. Furthermore, the electrical signal is a convenient trigger that can be used to start the data acquisition at the acoustic sensors.

Table 1—Time lag in electrical PD detectors

Type of detector	Time lag to t_0	Signal rise time (10% to 90%)	Approximate location error in oil
Wideband with active integrator (100-400 kHz)	0.2 μ s	1.2 μ s	Negligible (< 2 mm)
Narrowband at 1 MHz with 9 kHz bandwidth	16 μ s	35 μ s	22 mm to 70 mm (1 in to ~3 in)
Narrowband at 1 MHz with 4.5 kHz bandwidth	16 μ s	50 μ s	22 mm to 95 mm (1 in to ~4 in)

The major disadvantage of the combined system is that it may be difficult to obtain a clean electric PD measurement due to electrical noise in the field. Hence, the combined acoustic-electrical PD locator system is more suitable for use in the factory or plant than in the field.

4.3 On-line (continuous) acoustic monitoring system

The main purpose of permanently installed on-line acoustic monitoring systems is to provide an early indication of an incipient fault to a remote location. These systems usually consist of multiple sensors, amplifier, and data acquisition/processing modules. The sensors are placed at locations where faults may be anticipated based on past experience or highest probability of problems occurrence. The data acquisition/processing systems are able to transmit collected data and/or warning alerts to locations outside the substation.

The data is often limited to activity levels rather than specific waveforms. Location information is often limited to knowledge of which sensor is most active.

Some continuous monitoring systems use the signal from a split CT around the transformer case ground or a radio-frequency (RF) signal from a sensor inside the transformer to identify the AE signal as an internal PD.

Warning alerts caused by level of activity above a baseline or trend of activity are usually reason to take gas samples and perhaps perform more extensive acoustic or other testing.

5. Acoustic signal and transmission characteristics

5.1 Acoustic signal

The energy creating the acoustic signal is from PD and mechanical and thermal sources inside and outside transformers and reactors.

Figure 1(a) shows a waveform from an acoustic sensor mounted on the outside of a transformer tank. It is typical of one burst of PD. The sharp rise of the wave front indicates that a direct wave has impinged on the inside tank wall within the critical angle for a pressure wave.

The horizontal axis shows time in microseconds. The burst had a length of 144 μ s from the first threshold crossing to the last threshold crossing. The vertical axis is a dimensionless indication of amplitude. The number of acoustic bursts in a unit of time, usually 1 s, is a measure of acoustic activity.

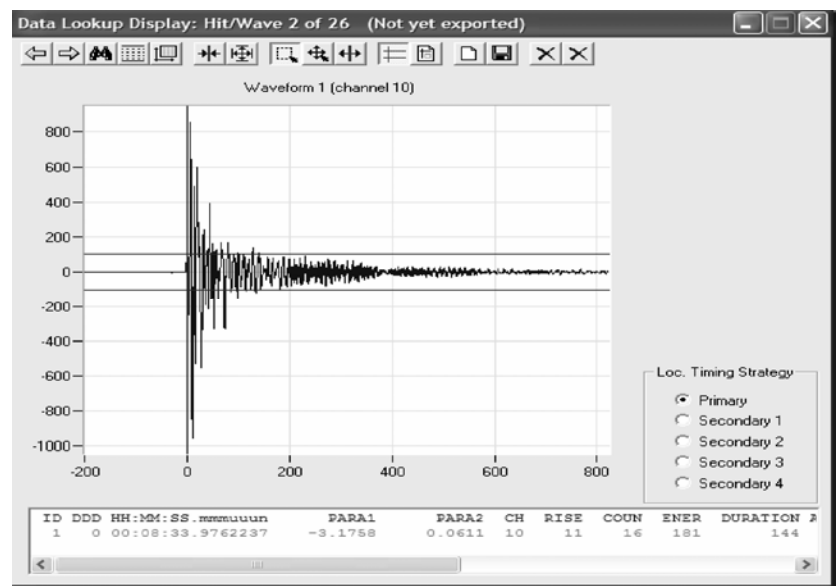


Figure 1(a)—Typical acoustic emission burst

Figure 1(b) is a detail of the waveform in Figure 1(a). There are 16 oscillations (also called counts) at or above the indicated threshold of ± 100 . The oscillations are shown as follows:

Oscillations: 1 2 3 4 5 6 7 8 9-10 11-12-13-14 15-16

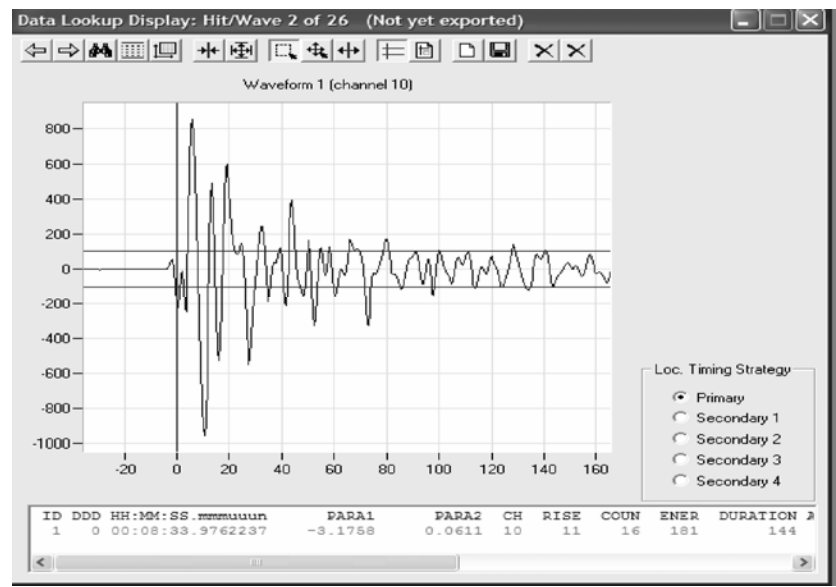


Figure 1(b)—Oscillations in an acoustic emission burst

AE detection systems may count bursts and/or oscillations.

In order to count bursts, the oscillatory portion of the decaying burst must be removed by means of a demodulation circuit or other means. This ensures that each emitted burst is recorded as a single discrete event. The bursts can then be recorded at a preset magnitude level over a 1 s time period. Also, a distribution of all the discrete AE burst magnitudes can be obtained by means of a pulse height analyzer, again over a 1 s time period. If the PD pulses occur faster than the ring-down time of the acoustic transducer or the time window used for pulse qualification in some automated systems, errors in burst rate count and burst height distribution will occur.

5.2 Acoustic signal propagation from source to tank wall

Active PD sources in oil-filled transformers produce AE signals that propagate away from the source in all directions. The acoustic signals travel through the intervening material to eventually arrive at the transformer tank wall. The distance traveled in a particular medium is dependent on the time that it takes for an acoustic signal to complete this journey as shown in the following equation:

$$\text{distance traveled} = \text{acoustic wave speed} \times \text{travel time}$$

Consequently, sensors placed at different locations on the tank wall, i.e., at different distances from the source, will experience different signal arrival times. For the case of the all-acoustic system, it is possible to detect the difference in signal arrival time at one sensor relative to another. This in turn allows for the estimation of the difference in the two propagation path distances. For the case of the combined acoustic-electric system, the time delay between the source and the sensor can be detected, and the absolute path length between the source and a given sensor can be determined. Each of these system types requires a slightly different procedure to locate the source, as described in Clause 8 and Clause 9.

Acoustic PD source location commonly assumes that the acoustic signal travels a direct, straight-line route from the source to the sensor. Unfortunately, this is not always the case as the acoustic field inside the tank is very complex due to wave reflection, diffraction in different materials, and other parameters. For example, if there is an obstruction blocking the line-of-sight between the source and the sensor location, the sound may travel around the obstruction. This results in a longer propagation time that would imply a greater distance between the source and the sensor than actually exists. Alternately, the sound may travel directly through the obstruction at a wave speed that is greater than in the oil. The resulting arrival time would be earlier, which would imply a shorter distance between the source and the sensor than actually exists. To help avoid these misinterpretations, it is important to confirm the estimated source location by repeating the distance calculations with several sensor locations.

5.3 Acoustic signal propagation within the tank wall

The propagation of the acoustic waves within the transformer wall is complex. However, using experimental evidence based on acoustic signals about 100 kHz and wall thickness about 10 mm, wave propagation velocity can be assigned a constant value and wave types can be regarded as similar to compression and shear waves. This empirical approach is used in this guide.

Structure-borne propagation paths within the tank wall present a further technical challenge. As the acoustic wave hits the tank wall, its frequency characteristics remain the same, but its mode of propagation and propagation speed change. In the example in Figure 2, the sensor is located on the far side of the tank, away from the source.

Primary reflection wave propagation can take place within the confines of the tank as shown in Figure 2. The speed of sound for this wave depends on the media encountered by the sound wave.