

IEEE Guide for the Detection, Location and Interpretation of Sources of Acoustic Emissions from Electrical Discharges in Power Transformers and Power Reactors

IEEE Power and Energy Society

Sponsored by the
Transformers Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std C57.127™-2018
(Revision of IEEE Std C57.127-2007)

IEEE Guide for the Detection, Location and Interpretation of Sources of Acoustic Emissions from Electrical Discharges in Power Transformers and Power Reactors

Sponsor

Transformers Committee
of the
IEEE Power and Energy Society

Approved 23 October 2018

IEEE-SA Standards Board

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

Keywords: acoustic emission (AE), attenuation, burst, gas-in-oil analysis, IEEE C57.127™, low-amplitude discharges, partial discharge (PD), power transformers, reactors

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2019 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 11 March 2019. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 978-1-5044-5469-8 STD23500
Print: ISBN 978-1-5044-5468-1 STDPD23500

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html>

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page, appear in all standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.” They can also be obtained on request from IEEE or viewed at <http://standards.ieee.org/IPR/disclaimers.html>.

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents (standards, recommended practices, and guides), both full-use and trial-use, are developed within IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (“IEEE-SA”) Standards Board. IEEE (“the Institute”) develops its standards through a consensus development process, approved by the American National Standards Institute (“ANSI”), which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE Standards are documents developed through scientific, academic, and industry-based technical working groups. Volunteers in IEEE working groups are not necessarily members of the Institute and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE Standards do not guarantee or ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

IEEE does not warrant or represent the accuracy or content of the material contained in its standards, and expressly disclaims all warranties (express, implied and statutory) not included in this or any other document relating to the standard, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; and quality, accuracy, effectiveness, currency, or completeness of material. In addition, IEEE disclaims any and all conditions relating to: results; and workmanlike effort. IEEE standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. The existence of an IEEE standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE should be considered the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE-SA Standards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, or be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position of IEEE.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE. However, IEEE does not provide consulting information or advice pertaining to IEEE Standards documents. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to comments or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in revisions to an IEEE standard is welcome to join the relevant IEEE working group.

Comments on standards should be submitted to the following address:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
Piscataway, NJ 08854 USA

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not imply compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under US and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate fee, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit the IEEE Xplore at <http://ieeexplore.ieee.org/> or contact IEEE at the address listed previously. For more information about the IEEE-SA or IEEE's standards development process, visit the IEEE-SA Website at <http://standards.ieee.org>.

Errata

Errata, if any, for all IEEE standards can be accessed on the IEEE-SA Website at the following URL: <http://standards.ieee.org/findstds/errata/index.html>. Users are encouraged to check this URL for errata periodically.

Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE-SA Website at <http://standards.ieee.org/about/sasb/patcom/patents.html>. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

Participants

At the time this guide was completed, the Detection on PD—Acoustic Emission Working Group had the following membership:

Detlev Gross, *Chair*
John Harley, *Vice Chair*

Omar Ahmed	Alexander Kraetge	Alaor Scardazzi
Jeffrey Benach	David Larochelle	Aron Sexton
Robert Brusetti	Gustavo Leal	Hemchandra Shertukde
Luc Dorpmanns	Gregorio Lobo	Andre Shor
Michael Franchek	Ali Naderian Jahromi	Charles Sweetser
Thang Hochanh	Arturo Nunez	Mark Tostrud
Stephen Jordan	Amitabh Sarkar	Marco Tozzi

The following members of the individual balloting committee voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

Tauhid Haque Ansari	Peter Kelly	John Roach
Stephen Antosz	Sheldon Kennedy	Zoltan Roman
Donald Ayers	James Kinney	Rodrigo Ronchi
Barry Beaster	Zan Kiparizoski	Ryandi Ryandi
Robert Beavers	Axel Kraemer	Dinesh Sankarakurup
Emil Bercea	Alexander Kraetge	Daniel Sauer
Enrique Betancourt	Jim Kulchisky	Roderick Sauls
Wallace Binder	Raja Kuppuswamy	Bartien Sayogo
Thomas Blackburn	John Lackey	Ewald Schweiger
William Bloethe	Chung-Yiu Lam	Hemchandra Shertukde
W. Boettger	Benjamin Lanz	Hyeong Sim
Alain Bolliger	David Larochelle	Jerry Smith
Demetrio Bucaneg Jr.	Michael Lauxman	Gary Smullin
William Byrd	Aleksandr Levin	Sanjib Som
Paul Cardinal	Mario Locarno	Brian Sparling
Suresh Channarasappa	Kumar Mani	Thomas Spitzer
Stephen Conrad	J.Dennis Marlow	Wayne Stec
Gary Donner	Lee Matthews	Craig Stiegemeier
Jorge Fernandez Daher	James McBride	Gary Stoedter
Namal Fernando	Mark McNally	Charles Sweetser
Bruce Forsyth	Susan McNelly	Juan Thierry
Anthony Franchitti	Andrew McNulty	Mark Tostrud
George Frimpong	Charles McShane	Marco Tozzi
Jalal Gohari	Joseph Melanson	James Van De Ligt
Edwin Goodwin	Daniel Mulkey	Ajith Varghese
William Griesacker	Ali Naderian Jahromi	Jason Varnell
Detlev Gross	K. R. M. Nair	John Vergis
Randall Groves	Lorraine Padden	Jane Verner
Bal Gupta	Bansi Patel	Dharam Vir
John Harley	Dhiru Patel	Loren Wagenaar
Roger Hayes	David Peelo	David Walker
Werner Hoelzl	Brian Penny	David Wallace
Philip Hopkinson	Christopher Petrola	David Wallach
Richard Jackson	Alvaro Portillo	Kenneth White
Nathan Jacob	Bertrand Poulin	Baitun Yang
John John	Iulian Profir	Peter Zhao
Stephen Jordan	Lakshman Raut	Leo Zibert
Laszlo Kadar	Johannes Rickmann	Waldemar Ziomek

When the IEEE-SA Standards Board approved this guide on 23 October 2018, it had the following membership:

Jean-Philippe Faure, *Chair*
Gary Hoffman, *Vice Chair*
John D. Kulick, *Past Chair*
Konstantinos Karachalios, *Secretary*

Ted Burse
Guido R. Hiertz
Christel Hunter
Joseph L. Koepfinger*
Thomas Koshy
Hung Ling
Dong Liu

Xiaohui Liu
Kevin Lu
Daleep Mohla
Andrew Myles
Paul Nikolich
Ronald C. Petersen
Annette D. Reilly

Robby Robson
Dorothy Stanley
Mehmet Ulema
Phil Wennblom
Philip Winston
Howard Wolfman
Jingyi Zhou

*Member Emeritus

Introduction

This introduction is not part of IEEE Std C57.127-2018, IEEE Guide for the Detection, Location and Interpretation of Sources of Acoustic Emissions from Electrical Discharges in Power Transformers and Power Reactors.

This guide is an expansion of IEEE Std C57.127™-2007. It has been expanded to add a detailed background theory, to better describe the different techniques available, and to add new applications of acoustic location. Documented case studies have also been added to highlight specific situations. Active workers in the field are constantly trying to improve their methods. More effective methods may appear in the future.

Contents

1. Overview.....	14
1.1 Scope.....	14
1.2 Purpose.....	14
1.3 Safety warning.....	14
2. Definitions, acronyms, and abbreviations	15
2.1 Definitions.....	15
2.2 Acronyms and abbreviations	16
3. Detection and measurement of PD—background information.....	17
4. Acoustic signal and transmission characteristics.....	18
4.1 Acoustic signal	18
4.2 Acoustic signal propagation	21
4.3 Velocity of sound in materials.....	23
4.4 Competing signal paths	24
5. AE systems—technical concepts.....	26
5.1 Introduction	26
5.2 All-acoustic system.....	26
5.3 Acoustic system with an electrical PD trigger.....	27
5.4 On-line (continuous) acoustic monitoring system	28
5.5 Acoustic sensors	29
5.6 Multiple sensors system	30
5.7 Band-pass filter.....	30
6. AE testing.....	30
6.1 General considerations on the application of sensors	30
7. AE field test procedure	32
7.1 Introduction	32
7.2 Test setup	32
7.3 Sensor placement and initial scan	32
7.4 Testing methodologies.....	33
7.5 Reporting and follow up	34
8. Factory test procedure	34
8.1 Introduction	34
8.2 Initial sensor placement.....	34
8.3 Measurements and changing of sensor placement.....	37
9. Characterization of AE signals	38
9.1 Introduction	38
9.2 HVDC transformers and reactors	38
9.3 Characteristics of PD from static electrification	39
9.4 Acoustic activity from thermal faults, the core, mechanical noises, and other sources	39
9.5 Application of acoustics during factory impulse test	40
10. Integrating AE results with data from oil analysis	41
11. Acoustic activity interpretation.....	43
Annex A (informative) Bibliography.....	45

Annex B (informative) Signal processing	51
Annex C (informative) Tutorial and case studies for detection and location of AE from PD	54

List of Figures

Figure 1—Typical AE burst.....	19
Figure 2—Oscillations in an AE burst.....	19
Figure 3—Acoustic signal showing pressure wave (1) and the slower shear wave (2) reflections from stiffener on a transformer tank. Lower trace (3) shows tank wall sound path without stiffener	20
Figure 4—Ultrasonic detection of air-borne PD signal using parabolic reflectors.....	20
Figure 5—“Original Defekt Sucher,” mechanical Instrument to investigate structural sound (~1930).....	21
Figure 6—“Textbook” triangulation, tank homogeneously filled and wall as thin membrane.....	22
Figure 7—Compression wave at a tank wall—aperture angle, possible travel paths.....	24
Figure 8—Shear wave at a tank wall—aperture angle, possible travel paths.....	24
Figure 9—Arrival of different wave fronts—fast tank wall path and straight oil path.....	25
Figure 10—Bolted magnetic wall shunts seated in rubber will block acoustic signals almost entirely.....	25
Figure 11—Hidden PD source—signal paths and assumed location.....	26
Figure 12—Example of HV-side of three-phase transformer assembly	35
Figure 13—Example of sensor locations with PD source in center phase. Typically sensors are located on each side wall.	36
Figure 14—Example of sensor locations with PD source in outer phase. Typically sensors are located on each side wall and on the end wall.	36
Figure 15—Example of sensor locations when phase of PD source is not known. Sensors are located initially on one side wall.....	37
Figure 16—Transformer tank—plan view	37
Figure 17—Response of lightning impulse as el. trigger (CH1) and acoustic signals (CH3+CH4).....	41
Figure B.1—Determining the starting time using the energy criterion.....	52
Figure B.2—Comparison of conventional (FFT) and high-resolution subspace method (MUSIC) for spectral analysis of “clear” (left) and strongly noised (right) AE burst from PD	53
Figure C.1—A PD source emits stress waves that are detected by a sensor on the tank wall. This signal is processed to validate that it is PD and to determine the location.....	54
Figure C.2—Views of the workstation screen showing PD hits versus time and the location of the source of PD in the transformer tank	56
Figure C.3—Internal flashover.....	56
Figure C.4—Acoustic activity and three-dimensional PD source location in a 330 MVA, 400/115/35 kV transformer	57
Figure C.5—Plot showing the time (horizontal) when the acoustic activity produces locatable events (vertical) for a portion of the test	58

Figure C.6—Load current versus acoustic activity	58
Figure C.7—Voltage profile	59
Figure C.8—Three-dimensional plots versus construction photographs showing two clusters of acoustic activity	60
Figure C.9—Internal inspection findings after unit failed	61
Figure C.10—PD pattern of paper layer delamination (flat gas-filled pockets)	61
Figure C.11—Using an HV cable as CC (left) and UHF drain valve sensor (right)	62
Figure C.12—Signal of three acoustic sensors based on electrical trigger signal (red)	62
Figure C.13—Triangulation results of the measurements as shown with Figure C.12	63
Figure C.14—High voltage cable box and found location of the PD activity	63
Figure C.15—PD pattern on X2—spherical gas bubble	64
Figure C.16—Acoustic location results on X2 LV with sensors underneath (left) and above (right) the tank	64
Figure C.17—Identified locations on the reverse switch of tap changer X1 and X2	65
Figure C.18—Faint acoustic signals in front of X2—wall shunt attenuation	65
Figure C.19—Shell-type core styles (top view)—standard (a) and five-limb variant (b)	66
Figure C.20—PD of a floating potential on HV C phase	66
Figure C.21—Faint acoustic signal as captured on the lower part of C coil	67
Figure C.22—Assumed construction of the coil stack and location of the static shields	67
Figure C.23—Acoustic signals as found at the top of coil 1	68
Figure C.24—Path of the acoustic signal through the oil channels under the pressure disk	69
Figure C.25—Travel path of the acoustic signal through the oil channels deeply into the winding	69

List of Tables

Table 1—Acoustic properties of various materials (Lundgaard [B45])..... 23

Table 2—Time lag in electrical PD detectors 28

Table 3—AE testing: field versus factory differences 31

Table 4—Comparison of electrical and acoustic PD signals 42

Table C.1—DGA history of the transformer with PD activity 56

Table C.2—DGA values..... 57

IEEE Guide for the Detection, Location and Interpretation of Sources of Acoustic Emissions from Electrical Discharges in Power Transformers and Power Reactors

1. Overview

1.1 Scope

This guide is applicable to the detection and location of sources of acoustic emissions (AEs) from partial discharges (PDs) and other sources in power transformers and power reactors. There are descriptions of acoustic instrumentation, test procedures, and interpretation of results.

1.2 Purpose

This guide is intended to provide information that may be helpful in planning, installing, and operating acoustic measuring equipment and in meaningful interpretation of resulting data.

1.3 Safety warning

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 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 emission 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 de-energized, but in no case should the transformer voltage be above normal voltage while the acoustic emission 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 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, acronyms, and abbreviations

2.1 Definitions

For the purposes of this document, the following terms and definitions apply. The IEEE Standards Dictionary Online should be consulted for terms not defined in this clause.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 (AE) monitoring (see 5.5).

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 (see 4.1).

¹IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>.

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), $Z = \gamma \times v$.

AE burst rate: Denotes the actual number of discrete AE events or bursts per unit time, usually one second, or per cycle of the ac voltage wave.

AE burst: A group of AE oscillations constituting a transient signal (see 5.5).

AE oscillation rate or count rate: The number of AE oscillations that exceed the counter threshold level in a time interval, often one second, or a number of cycles, depending on the instrument being used (see 4.1).

AE oscillation: An oscillation produced by a resonant piezo-electric crystal when perturbed by a pressure wave, which could be caused by an electrical discharge or other source.

Barkhausen effect: The non-uniform, hence non-linear, flipping of the magnetic domains during magnetization (see 9.4).

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

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

magnetostriction noise: A linear property of the magnetic material that undergoes a deformation due to the magnetic forces (see 9.4).

pressure waves: These waves consist of alternate compression and rarefaction forces in the direction of propagation. They occur in both liquids and solids. *Syn:* **longitudinal waves**.

shear waves: A pressure wave in the insulating liquid 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. Shear waves require an acoustically solid material for effective propagation so do not exist in liquids, but can be found in any solid transformer material, such as metal, pressboard, or wood for instance. *Syn:* **transverse waves**.

speed of sound in steel: Longitudinal wave about 5900 m/s; transverse wave about 3200 m/s, respectively.

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

2.2 Acronyms and abbreviations

AE	acoustic emission
CC	coupling capacitor
CT	current transformer
DGA	dissolved gas analysis
FFT	Fast Fourier Transform
HRSA	high-resolution spectral analysis
HV	high voltage
HVDC	high-voltage direct-current

JTFA	joint time-frequency analysis
LTC	load tap changer
LV	low voltage
MV	medium voltage
OLTC	on-load tap changer
PD	partial discharge
RF	radio frequency
RFCT	radio-frequency current transformer
RIV	radio-influence voltage
SNR	signal-to-noise ratio
UPS	uninterruptible power source
UV	ultraviolet

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 for power transformers and reactors 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. The corona type of PD emits mostly up to a frequency of approximately 300 MHz.
- 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. Signals are strongly attenuated when they pass through the bushings or travel longer distances between the source and the transformer. Cell phone and TV stations operate in the UHF band and might introduce strong noise unless the antenna is shielded. Discharges directly in the oil have an upper frequency limit of only a few hundred kilohertz and cannot be detected by UHF. However, it is likely that gas or bubbles will be produced and will make PD measurable by UHF.
- c) Radio-frequency current transformers (RFCTs): 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. Installation is simplified with the use of clamp-on RFCT. It can be used both for off-line and online measurement states.
- d) Coupling capacitor (CC): The CC sensor interfaces directly with the voltage terminal. This is the method described in IEC 60270 [B37], IEEE Std C57.113™-2010 [B40]. 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 condenser layered bushing seen at the capacitive tap as the CC. When the user supplies an external reference capacitor for online measurements, the measurement is considered intrusive.
- e) Acoustic emission (AE): Consists of one or more ultrasonic receiving transducers that are sensitive to the AE generated by an electrical 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 PDs in cellulose, although usually in lower quantities than the other gases (Dahlgren and Harley [B17], Duval and dePabla [B19]). 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 electrical discharges using AE techniques. These techniques are sometimes combined with one or more of the previously listed PD detection and measurement methods.

4. Acoustic signal and transmission characteristics

4.1 Acoustic signal

The electron avalanche of a PD event releases energy that causes a local heating of the gas or other material and, hence, causes a rapid local pressure increase. The spectrum of the resulting sound extends into several MHz (Lundgaard “Partial Discharge—Part XIV” [B45]). The resulting pressure wave or longitudinal wave propagates through the medium at a certain speed, which is a property of the medium and is being influenced by other parameters, for example, the temperature.

Figure 1 shows a waveform from an acoustic sensor mounted on the outside of a transformer tank. It is typical of one burst of PD. The rapid rise of the wave front, followed by a decay, 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 μs from the first threshold crossing to the last threshold crossing.

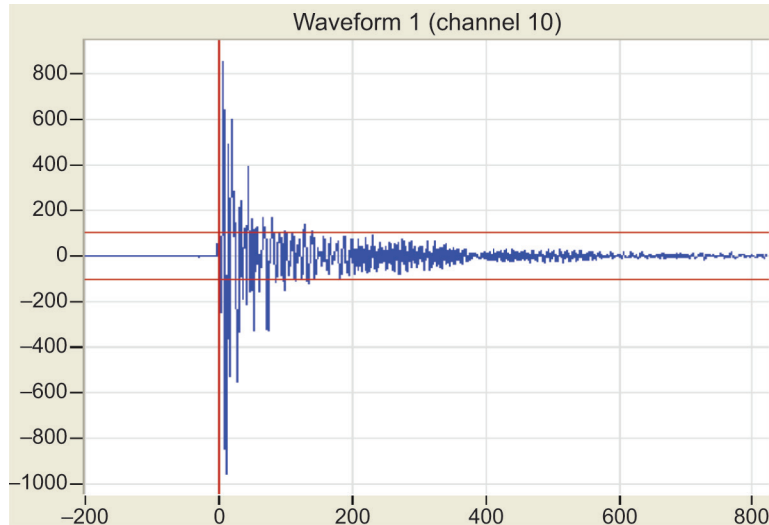


Figure 1—Typical AE burst

The vertical axis is an indication of amplitude, which can be measured in volts and shown as decibel or volts. The number of acoustic bursts in a unit of time, usually one second, is a measure of acoustic activity.

Figure 2 is a detail of the waveform in Figure 1. There are 16 oscillations (also called counts) at or above the indicated threshold of ± 100 .

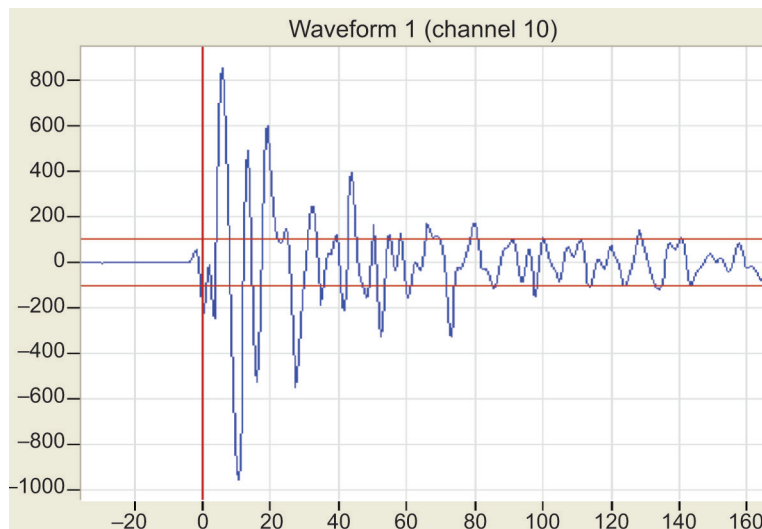


Figure 2—Oscillations in an AE burst

In solid materials, such as steel used for transformer tanks, shear waves velocity (typically 3200 ms^{-1}) is substantially lower than pressure waves (typically 5900 ms^{-1}) (Lundgaard [B44], [B45]). Because the shear wave arrives later, it is typically buried in the signal of the pressure wave and, therefore, usually not of importance for detection and location. Figure 3 shows an example of the pressure wave (Figure 3, callout 1) and the slower shear wave (Figure 3, callout 2) acquired on a transformer tank wall (upper trace). Here, additionally, a fin-style tank wall stiffener causes the reflected signal.

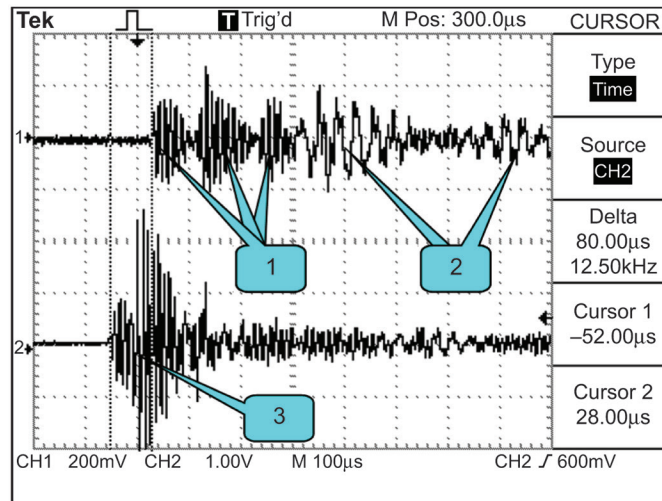


Figure 3—Acoustic signal showing pressure wave (1) and the slower shear wave (2) reflections from stiffener on a transformer tank. Lower trace (3) shows tank wall sound path without stiffener

For the detection of air-borne sound of PD activity, different types of microphones are suitable and have been used. Typically, parabolic reflectors, as shown in Figure 4, are used in order to amplify the usually faint acoustic signals and to obtain directivity for locating the source. Often, such devices are equipped with notch and bead sighter or a laser pointer to aim the device for identification of the source. Using higher frequencies improves the directivity, as the wavelength becomes shorter. Thus, usually, ultrasonic frequencies are used. The majority of commercially available sensors operate at 40 kHz resulting in a wavelength of 8.5 mm for 340 ms^{-1} , which does not limit the location precision. The devices are equipped with circuits to convert the ultrasonic signal into audible sound and come with speakers or headsets.

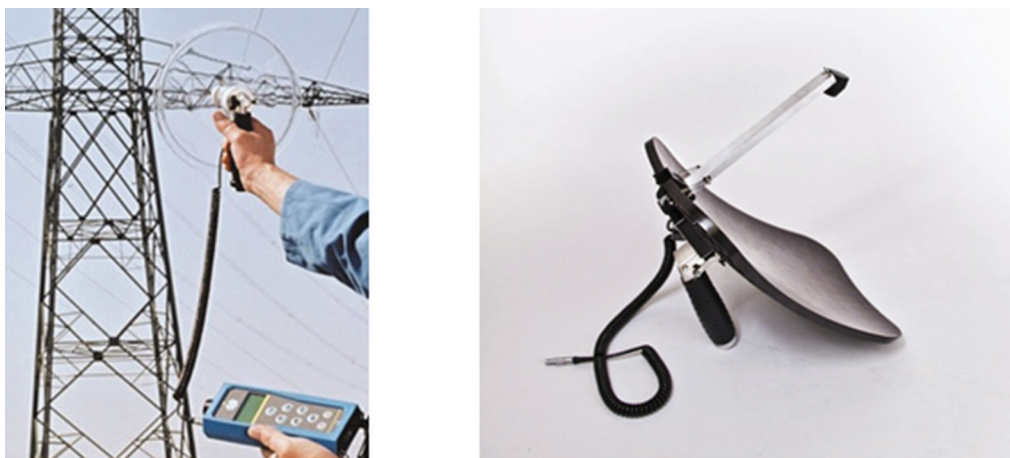


Figure 4—Ultrasonic detection of air-borne PD signal using parabolic reflectors

For the acquisition of structural sound, such as with gas-insulated switchgear, cable accessories, or transformer tanks, stethoscope-like instruments were in use in the 1930s to mechanically guide and amplify sound signals (Figure 5). Versions with rods made of insulating material were available to investigate test objects on moderate high voltage (Gross “Acoustic Location...” [B25]).



Figure 5—“Original Defekt Sucher,” mechanical Instrument to investigate structural sound (~1930)

Nowadays, typically, piezoelectric sensors are used to acquire such signals. Jacques and Pierre Curie found the piezoelectric effect about 1880 [B16]. In 1916 research was conducted to use the principle for detecting submarines. However, widely industrial applications of piezoelectric sensors did not start until the 1950s.

At its inception, the AE of PD in liquids and solids can be considered as a steep impulse with a slower decay and, hence, the spectral amplitude of the resulting signal shows decaying amplitude with increasing frequency. Therefore, the highest sensitivity can be achieved toward the lower frequencies.

However, acoustic signals originating from mechanical sources also show predominantly higher signal amplitudes in the lower frequency range. Moreover, impulse sound originating from the changing size and orientation of magnetic domains in core material, the so-called Barkhausen noise (Bartnikas and McMahon [B6]; Howells and Norton “Detection of Partial Discharges...” [B35]; Clatterbuck, et al. [B14] reaches well into several tens of kHz. Selection of the proper acoustic sensor and its frequency range is always a compromise and strongly depends on the application and signal processing technology used.

4.2 Acoustic signal propagation

Generally, pulse-like AE due to PD activity travels well in liquids, such as the oil of a liquid filled power transformer. In liquids, the pressure wave from a point source (such as PD) travels with a spherical wave front. As any radiation having a spherical wave front, the acoustic signal undergoes a progressive decay with increasing distance from the source, also known as free space path loss (provided that there are no obstacles). However, this distance-dependent decrease is not a loss per se, but rather a decrease due to the fact that the signal power is spread over the increasing surface of the spherical wave front, as shown in Equation (1):

$$S = P_i \frac{1}{4\pi d^2} \quad (1)$$

where

- S is the power per area at a sensor
- d is the distance of a source
- P_i is the power of the source