PD IEC/TS 62478:2016

BSI Standards Publication

High voltage test techniques — Measurement of partial discharges by electromagnetic and acoustic methods

National foreword

This Published Document is the UK implementation of IEC/TS 62478:2016.

The UK participation in its preparation was entrusted to Technical Committee PEL/42, Testing techniques for high voltages and currents.

A list of organizations represented on this committee can be obtained on request to its secretary.

Published by BSI Standards Limited 2016

ISBN 978 0 580 76776 0
ICS 17.220.20; 19.080

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 30 September 2016.

Amendments/corrigenda issued since publication

Date	Text affected

IEC TS 62478

Edition 1.0 2016-08

TECHNICAL SPECIFICATION

SPECIFICATION TECHNIQUE

colour
inside

High voltage test techniques – Measurement of partial discharges by electromagnetic and acoustic methods

Techniques d'essais à haute tension – Mesurage des décharges partielles par méthodes électromagnétiques et acoustiques

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 17.220.20; 19.080

ISBN 978-2-8322-3560-7

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

HIGH VOLTAGE TEST TECHNIQUES – MEASUREMENT OF PARTIAL DISCHARGES BY ELECTROMAGNETIC AND ACOUSTIC METHODS

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.

3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.

4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.

5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.

6) All users should ensure that they have the latest edition of this publication.

7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.

8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.

9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a technical specification when

- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62478, which is a technical specification, has been prepared by IEC technical committee 42: High-voltage and high-current test techniques.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
42/325/DTS	42/333/RVC

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

Partial discharges (PDs) generate electromagnetic and acoustic waves, emit light and produce chemical decomposition of insulation materials; these physical and chemical effects can be detected by various diagnostic methods and appropriate sensing elements (sensors). Besides the so-called ‘conventional’, electrical method described in IEC 60270, it is possible to detect and measure PDs with various ‘non-conventional’ methods (see Annexes A and B).

There is a special need to give recommendations for two used non-conventional methods, acoustic and electromagnetic ones, and this document is the first step in this direction.

HIGH VOLTAGE TEST TECHNIQUES – MEASUREMENT OF PARTIAL DISCHARGES BY ELECTROMAGNETIC AND ACOUSTIC METHODS

1 Scope

This document is applicable to electromagnetic (HF/VHF/UHF) and acoustic measurements of PDs which occur in insulation of electrical apparatus.

This specification deals with a large variety of applications, sensors of different frequency ranges and differing sensitivities. The tasks of PD location and measuring system calibration or sensitivity check are also taken into account.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 60034-27, *Rotating electrical machines – Part 27: Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines*

IEC 60270, *High-voltage test techniques – Partial discharge measurements*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
partial discharge
PD
complex physical phenomena consisting of a localized electrical discharge caused by partial breakdown of an insulating medium under the influence of the local electrical field stress

3.1.1
partial discharge current pulses
PD current pulses
extremely fast current pulses, whose rise time and pulse width depend on the discharge type, defect type, geometry and gas pressure

3.1.2
electromagnetic effects of PD
PD current pulses resulting in the emission of transient electromagnetic waves at very high frequency ranges

Note 1 to entry: The electromagnetic waves generated by PD signals propagate through the dielectric materials which surround the PD source; these signals can be detected by various antennas or transducers (sensors).

3.1.3
acoustic effects of PD

transient acoustic wave resulting from the super-heated gas channel produced, similar to lightning, by a PD current pulse

3.1.4
detection and measurement of effects of PD

activities that can be detected and measured using the following methods:

- electrical methods: conventional (according to IEC 60270) or electromagnetic (HF, VHF and UHF) methods
- acoustical methods
- optical methods
- chemical methods

Note 1 to entry: Measurement of PD activity is an important criterion for the evaluation of the dielectric condition of insulation systems of electrical apparatus.

Note 2 to entry: This document only discusses electromagnetic and acoustic methods.

3.2
PD measuring system

measuring system for unconventional PD detection consisting of sensing element, transmission path and measuring instrument

3.2.1
sensing element

sensor or antenna and connection link (e.g. electric or fiber optical cable) to the measuring instrument

3.2.2
transmission path

path characterized by the following parameters:

- distance from the location of the PD to the sensor
- type of PD signal transmission (conducted or field coupled)
- propagation characteristic of dielectric material(s) such as dispersion, attenuation, resonances, reflection, diffraction

3.2.3
PD measuring instruments

instruments that utilize various combinations of digital and analog techniques to display partial discharge signals in order to assist in their interpretation and evaluation

Note 1 to entry: The measured PD signals are influenced by different behavior of dielectric medium (gaseous, liquid or solid) for acoustic or electromagnetic signal propagation and offer different possibilities for data evaluation in the time and frequency domains, depending on different bandwidths of the sensing element and measuring instrument.

3.3
PD measurement system checks

complex combination of equipment whose proper and correct operation is ascertained by performance checking methods

3.3.1
performance check
check serving to assure correct functioning of the entire measuring system, from sensor to PD measuring instrument, typically by injection of an artificial signal

Note 1 to entry: The time and frequency domain characteristics of the injected artificial signal(s) used for the performance check are chosen to appropriately emulate the PD phenomenon being measured along with the parameters of the PD measuring system, e.g. bandwidth, type of sensor, etc.

Note 2 to entry: In carrying out the performance check, it is not necessary to emit electromagnetic or acoustic waves into the test object, that is to say, single-port checks are possible.

3.3.2
sensitivity check
check used to establish the quantitative correlation between the apparent charge of the PD event (in units e.g. pC) and the quantity measured and displayed by the electromagnetic or acoustic PD measurement system, typically by injection of an artificial signal

Note 1 to entry: The time and frequency domain characteristics along with the amplitude of the artificially injected signal(s) used for the sensitivity check are typically derived from a laboratory measurement in which the output of the electromagnetic or acoustic PD measurement system is simultaneously compared with the measurement of an actual PD source in an IEC 60270 test set-up.

Note 2 to entry: In carrying out the sensitivity check, it is necessary to emit electromagnetic or acoustic waves into the test object in order to emulate actual PD signals.

3.4
quantities and units

3.4.1
sensor output voltage
response of electromagnetic or acoustic sensor expressed in V or dBmV

3.4.2
sensor effective aperture
ratio between maximum sensor output power and power density of the incoming electrical field

Note 1 to entry: The sensor effective aperture is expressed in mm^2.

Note 2 to entry: In this case the measured quantity is the pulse energy arising from a transient electric field produced by the PD signal.

3.4.3
sensor effective height
sensor effective length
ratio between the sensor's output voltage magnitude (in V) to the incoming electric field strength (in V/mm)

Note 1 to entry: The sensor effective height is expressed in mm^2.

Note 2 to entry: The typical output consists of a transient voltage pulse.

3.4.4
antenna factor
inverse of the effective height or length defined as ratio between incoming electric field strength (in V/mm) to the sensor's output voltage magnitude (in V)

Note 1 to entry: The antenna factor is expressed in mm^{-1}.

4 Electromagnetic PD phenomena

4.1 Physical background

The short rise times of PD pulse currents (<1 ns) excite electromagnetic waves ranging from HF up to the UHF range (3 MHz up to 3 GHz) and exceeding in several insulation materials. The propagation velocity of the resulting UHF waves is dependent on the resulting ε_r, e.g. in oil estimated to about $2/3 \times c_0$ or 2×10^8 m/s (c_0 denoting the speed of light in a vacuum). The measurement frequency range depends on the specific apparatus.

4.2 Transmission aspects

Metal parts of apparatus enclosures can act as waveguides or resonators and effects such as dispersion, attenuation, cavity resonances, standing waves, reflection and diffraction all influence the propagation of the PD pulse signals and the pulse characteristics respectively.

Transmission path characteristics typically depend on

- material characteristics and dimensions,
- electromagnetic impedance and dielectric behavior of the surrounding dielectric medium,
- distance between source and sensor.

4.3 Measuring systems

4.3.1 Electric/electromagnetic fields

Non-conventional PD measurement systems based on radio frequency (RF) techniques operate in two different modes; one uses the frequency range in the HF/VHF area and the other uses the frequency range in the UHF area. In the HF and VHF range electric, magnetic and electromagnetic field (e.g. TEM_{00}) can typically be measured. In the UHF range predominantly the electromagnetic field modes (e.g. TEM_{xx}) are measured.

4.3.2 Frequency ranges

HF nominally covers the frequency range from 3 MHz to 30 MHz and VHF the frequency range from 30 MHz to 300 MHz. Typical measuring bandwidths for narrow band measurement in the HF and VHF range up to 3 MHz, for wide band measurement in the VHF range, typically 50 MHz and higher, respectively.

The UHF frequency range is nominally between 300 MHz to 3 GHz. The measuring mode applied in the UHF range is typically either the zero span mode at one or several individual frequencies with the resolution bandwidth typically between 3 MHz to 6 MHz, or the full bandwidth mode.

4.3.3 Sensors

4.3.3.1 General

Typically used sensors in the HF and VHF frequency range are based on capacitive, inductive and electromagnetic detection principle.

In the UHF frequency range, the sensors used are typically near-field antennas such as disc or cone shaped sensors along with field grading electrodes.

The sensor output signals are typically in the form of high frequency oscillating pulses. These signals can be displayed in the time domain as oscillating pulses with e.g. the maximum of the envelope the measured output quantity. In the frequency domain the signals are typically displayed as the spectrum resulting from the transient pulses. The measured output quantities in the frequency domain are the maximum magnitudes of the related characteristic spectral frequencies.

Sensors can be characterized as high frequency impedances consisting of a combination of capacitive, inductive and resistive component values. This high frequency impedance and the corresponding measuring frequency range determine the sensor's measuring mode and the resulting output is a function of its impedance and the magnitude of the related transient field component arising from the PD signal.

The measured quantity can be a transient voltage or current pulse value.

4.3.3.2 Type and characteristic

Some examples of sensors predominantly used in HF up to VHF frequency ranges:

- capacitors;
- current transformers;
- Rogowski coils;
- directional electromagnetic couplers;
- film electrodes;
- axial field couplers;
- transient earth voltage (TEV) probes;
- resistive couplers.

Some examples of sensors mainly used in the UHF range:

- disc and cone-shaped sensors;
- external window couplers;
- hatch couplers;
- barrier sensors;
- field grading electrodes;
- wave guide sensors;
- UHF antennas;
- directional electromagnetic couplers.

The output quantity of the sensors can be classified into the following groups:

- frequency characteristic, i.e. transfer function;
- polarity maintaining;
- directional;
- field magnitude dependent;
- sensitivity;
- installation dependent on geometry and location;
- mode dependent;
- transfer characteristic;
- monitored area which shall be in the range of the receiving area of the sensors.

4.3.3.3 Position

Sensors can be installed inside the high voltage component or externally mounted at dielectric apertures as e.g. inspection windows or valves. The sensors should be installed as close as possible to the particular PD detection area and inside the metallic enclosure or screen of the high voltage component.

In larger high voltage apparatus or systems it is beneficial to install multiple sensors to improve measurement sensitivity and to help in PD source detection and location. Multiple sensors can also be used for the sensitivity check of the arrangement.

The sensors should not have any negative impact to the dielectric design and functionality of the high voltage component.

4.3.4 Instrument related influences

4.3.4.1 Frequency and time domain signal processing

The output signals of the sensors can be processed in the time or frequency domain (see Figure 1).

Broadband time domain signal processing better represents the complete wave shape of the PD related pulse and enables detailed analysis of wave shape characteristics of individual single pulses (e.g. PD reflectometry, PD pulse shape analysis, etc.).

Narrow-band frequency domain signal processing may allow a better noise suppression capability should noise and external disturbances be present and consequently features an improved sensitivity in noisy environments. A single pulse wave shape analysis is not fully possible since bandwidth limitations in the processing path corrupts pulse shapes although derived statistical analysis as e.g. phase resolved PD pattern can be applied.

4.3.4.2 Processing bandwidth

The time domain processing uses a wide or ultra wide frequency range for signal processing. Filters to suppress single or multiple interferences are applied before signal processing. The signal is then processed from a wide band peak detector and displayed in the time domain typically synchronized with the phase of the applied high voltage.

Frequency domain processing is typically carried out either at various frequency spans or in zero span mode, essentially a tuned receiver centered at a fixed center frequency with a specific resolution bandwidth. The output of this zero span mode is typically displayed in the time domain e.g. similarly to a typical oscilloscope display or e.g. as a PD phase resolved pattern.

The wideband spectral mode processes the output of either a swept frequency receiver (i.e. super heterodyne) or a so-called ‘real-time spectrum analyzer’ as a power spectrum versus frequency. This can also be displayed as a spectrum of the measured signals (PD and other signals).

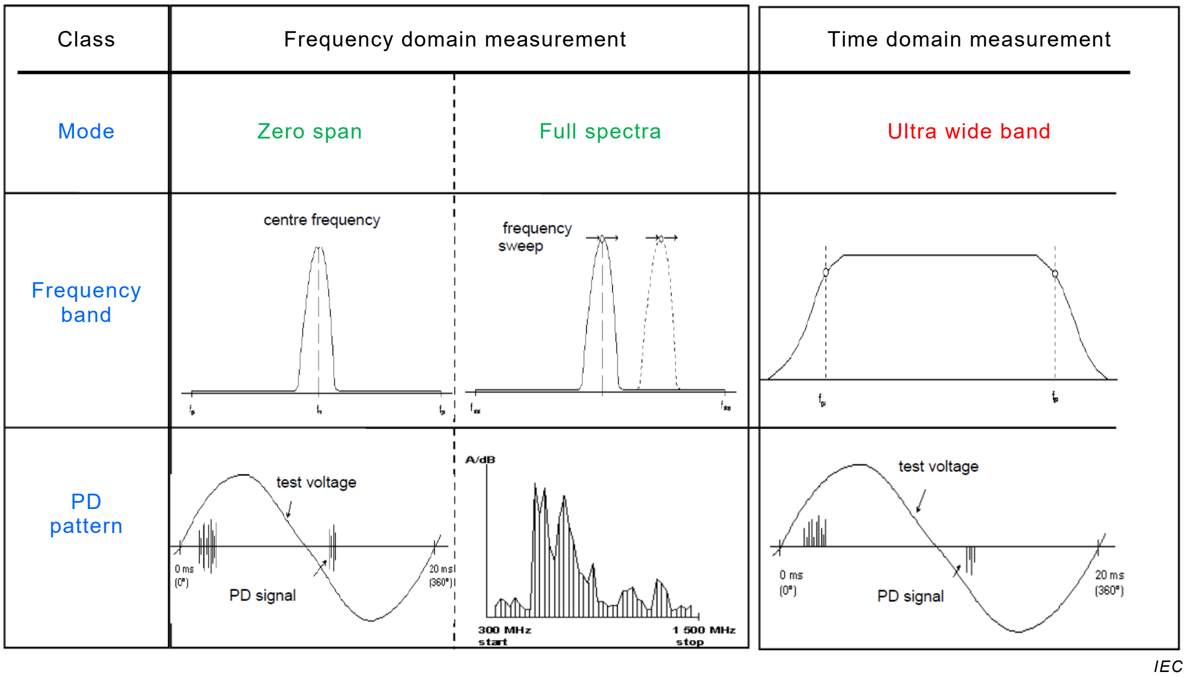


Figure 1 – Classification of instruments for signal processing

4.3.5 Instrument quantities

In HF and VHF ranges the instrument quantities are typically amperes or volts considering the application of inductive and capacitive couplers. The output of UHF sensors is also typically a voltage signal. These values measured by the instruments are in linear correlation to the measured electromagnetic field mode and the sensor transfer characteristic.

Derived quantities however should be in correlation to the PD parameters. This can be linear, when using the direct output voltage of the UHF sensor, or quadratic, e.g. by processing the power quantity (W) of the sensor signal, or the signal energy (J) as related to the defined measuring resistance

NOTE The UHF sensor can be described with its antenna characteristic in terms of its effective height (m), effective aperture (mm^2), antenna factor (1/m) or antenna gain (dBi).

4.3.6 Performance and sensitivity check

For detecting and measuring the electromagnetic waves emitted by partial discharges, different aspects of the method are shown in Figure 2.

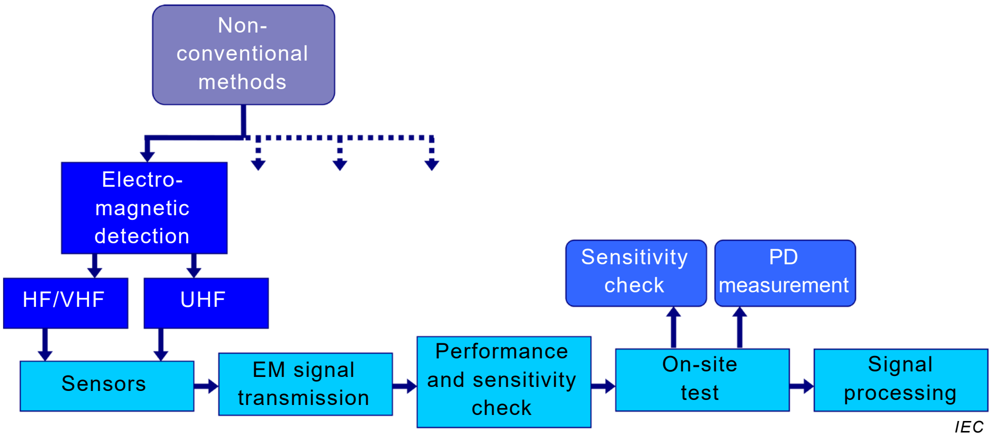


Figure 2 – Overview of the important aspects of electromagnetic PD detection

It should be emphasized that when employing the electromagnetic detection (radio frequency) method, the PD magnitude as apparent charge cannot be evaluated directly as a calibrated value.

However, a verification of the detection sensitivity can be performed and has proven to be useful in practice, e.g. for gas-insulated switchgear, rotating machines stator windings, etc. In Figure 3 the general steps for performing a sensitivity check for GIS, power transformers, stator windings and power cables are shown. Although the specific steps on different high voltage apparatus differ slightly, the general approach is shown in Figure 2.

To evaluate the detection sensitivity of the electromagnetic e.g. UHF method, the sensitivity check should be applied. With this the achievable detection sensitivity is demonstrated in a worst-case configuration by direct comparison in a simultaneous IEC 60270 measurement of apparent charge (pC) from an actual, significant and meaningful PD source.

The performance check is a functional check of the whole measuring PD system and does not relate to apparent charge measurements in general.

NOTE The performance check also can be used for finding suitable narrow-band measurement frequencies.

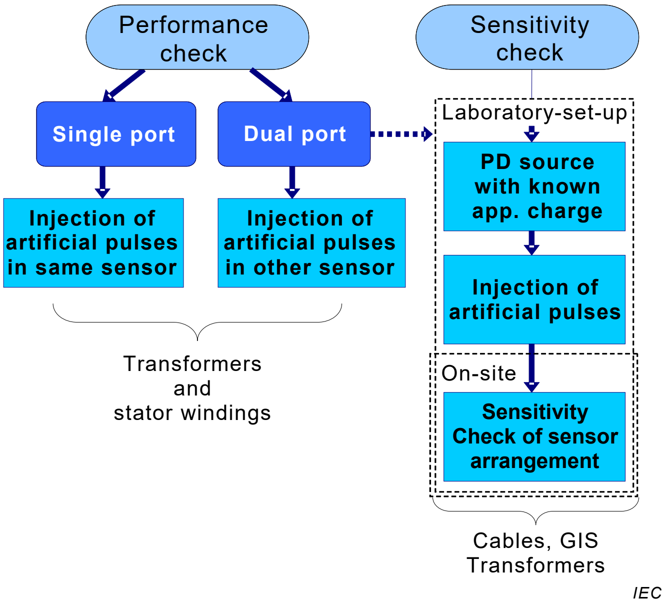


Figure 3 – Overview of performance and sensitivity checks in different apparatus

The PD detection in the HF up to UHF range is mainly applied for power cable accessories and rotating machines where the electromagnetic transients are captured by means of inductive and capacitive sensors as well as by special designed field probes. For power transformers, gas-insulated switchgear and stator windings, VHF and UHF ranges are primarily used.

5 Acoustic PD phenomena

5.1 Physical background

Acoustic PD detection is based on the fact that PD appears as a point source of acoustic waves. These acoustic waves spread through the internal structure of the high voltage apparatus until reaching the external surface. Different wave types with different propagation velocities appear and also reflections and refractions at boundaries result in attenuation, absorption and scattering effects. Typically the acoustic waves are detected and converted into electric signals typically by means of piezoelectric sensors, structure-born sound-resonance-sensors, accelerometers, condenser microphones or opto-acoustic sensors. Acoustic PD related signals might also be generated from free moving particles in gas insulated apparatus (e.g. GIS).

For PD detection, typically the ultra-sonic frequency range is employed (approximately 20 kHz to 250 kHz), as well as the audible range (approximately 100 Hz to 20 kHz). The frequency ranges used for acoustic detection are chosen depending on the insulation system to which the method is being employed (solid, liquid and gaseous).

5.2 Transmission path aspects

Within liquid and gaseous insulation parts, the radiated sound field ideally propagates as a spherical pressure (longitudinal) wave. When reaching solid insulation parts or enclosures, more complicated modes and so-called structure-borne propagation paths will typically be observed. The acoustic waves have different velocities in different media. Due to this, the geometrically shortest propagation path may not necessarily be the fastest path taken between source and sensor.

The acoustic transmission path typically includes the following very important characteristics:

- propagation modes of the acoustic wave and variations thereof along the transmission path from source to sensing element;
- variations in propagation velocity depending on different materials and conditions (e.g. for insulating oil: comparatively high velocity variation with temperature, only minor velocity variation with humidity);
- dispersion: frequency-dependency of propagation velocity;
- frequency-dependent attenuation of acoustic pulses in various insulation material or compounds and structures;
- matching of acoustic impedances at material boundaries e.g. between the sensing element and high voltage apparatus housing;
- distance from sensing element to PD origin.

5.3 Measuring system

5.3.1 General

Measuring systems can be divided into contact and non-contact (or distance) ones. For sensitive detection of PD inside high voltage apparatus, measuring systems employing direct contact between their sensors and the structures of the apparatus e.g. the housing are predominantly used.

Furthermore the measuring systems can be also differentiated based on whether time-domain or frequency-domain processing is employed.

5.3.2 Sensors

5.3.2.1 General

Available sensors can be divided into piezoelectric sensors, microphones or sensors using acoustic-optical effects.

Two types of externally mounted piezoelectric sensors exist:

a) accelerometers (output signal proportional to acceleration) with flat frequency characteristic;
b) acoustic emission sensors (output signal proportional to velocity) which typically exhibit dominant resonances in their frequency characteristic.

5.3.2.2 Type and characteristic

There are passive or active sensors (meaning with signal amplification in the sensor housing). Generally a significant level of signal amplification close to the sensor element is most beneficial depending on characteristics of the sensing element.

General characteristics of a sensor comprise:

- sensitivity,
- frequency characteristics as a working range of frequencies (resonant type or flat frequency response),
- temperature characteristics as a working range temperatures.

In view of the attenuation of acoustic signals, often sensors of resonant type with their characteristic higher sensitivity in specific frequency ranges are preferred.

5.3.2.3 Positioning of acoustic sensors for PD detection

Generally external acoustic piezo-electric sensors should be positioned where they have the best chance to pick up acoustic signals being generated by PD, i.e. where the structure best transmits vibrations. Thus the sensors can be positioned close to areas which possibly may have showed problems in prior tests.

NOTE **GIS:** Acoustic signals are picked up by sensors placed on the external surface of the GIS enclosure. Typically the sensors are affixed to the enclosure either by elastic bands or magnetic holders. Because the acoustic signal arriving from the defect(s) undergoes attenuation along the length of the GIS, especially when there are e.g. spacers between the PD source and the measuring probe, the sensor is usually positioned in different locations of the GIS (typically at least one measuring point in every compartment).

Transformers: Valuable information for positioning of sensors can be gained by referring to the design of the transformer. It is advantageous to avoid locations for sensor positioning e.g. close to or directly on top of stiffening ribs of the transformer housing, and instead choose areas between mechanical reinforcement elements of the transformer housing. Safety distances should be taken care of when placing sensors in the upper part of the transformer tank. Also, the sensors may be moved around during the process of determining the location of the PD within the enclosure.

5.3.3 Instrument quantities

The main unit to quantify mechanical pressure is the Pascal. However, the piezo-electric sensors predominantly used convert incoming acoustic waves into voltage output signals related to the mechanical input; hence the quantity measured in most of the instruments is either by volts (V) or decibels (dB).

Additionally, other derived values may be used to interpret the acoustic data, for example pulse rate or pulse count, histograms, pulse patterns synchronized with the phase of the applied high voltage, frequency domain information of single or multiple acoustic PD pulses, different correlation factors to power frequency and others.

5.3.4 Performance and sensitivity check

As for the UHF method the acoustics signals can be measured either in the time or in the frequency domain. The sensitivity verification is intended to verify the specific measuring equipment and can be performed in a two-step procedure.

Step 1 – Laboratory tests

As in the case of the UHF method, laboratory tests are first performed to determine the frequency spectrum and signals levels from a real PD defect. The acoustic signal level corresponding to a known discharge level in pC of apparent charge from a real PD source is recorded with the sensor and instrument to be used. Furthermore, the frequency spectrum of the detected signal should also be measured.

Next, the signal from an artificial acoustic signal emitter is recorded by the acoustic measuring device. The signal can be produced by an acoustic sensor (piezo-crystal) used in reverse method (i.e. pulsed by a step voltage). If the frequency spectrum as well as the signal intensity from the artificial source can be established in such way that they are similar to that from the real defect, a reference that can be used for the sensitivity verification is established. For the piezo-crystal, this may be achieved by using a well-chosen sensor pulsed with a step voltage whose magnitude and rise time have been adapted for the purpose.

If the frequency characteristic of the signal from the artificial source differs from that of the real defect, then a filter shall be inserted between the pick-up sensor and the signal conditioning and recording unit to limit the detected frequencies to the range relevant for the real defect.

NOTE When performing acoustic measurements, a 3 dB variation in sensitivity typically occurs simply due to removing and re-fixing the sensor. Also, the acoustic waves are highly dispersive. Therefore such measurements will only be suitable for verification and not for a calibration.

As an alternative to the piezo-crystal a steel ball with a diameter in the mm range dropped a fixed distance on the enclosure may be used as an emitter. This method will excite a wider frequency band signal than the method using a pulsed piezoelectric crystal. Breaking a pencil lead on the structure surface has proved to be a suitable method as well.

Step 2 – On-site tests

To verify the sensitivity and the integrity of the measuring equipment on-site, the enclosure shall be excited in the same way as in the laboratory. The entire measuring system shall be the same as that employed during the laboratory test.

6 Location of PD sources

6.1 General

When performing PD measurements on high-voltage devices, two different approaches for locating the source of the PD are typically employed. Firstly, alterations of the signal amplitudes or deformations of the signal shapes can give indications of the PD source location. Secondly, measuring the propagation times of PD pulses can be used to calculate source locations. Such methods are also referred to as arrival-time-based location or time-of-flight measurements. Methods based on electromagnetic, acoustic or a combination of both techniques can be employed.

When using arrival-time-based location methods, normally an underlying mathematical description or modelling is applied to determine the spatial PD location. Observation equations range from linear difference equation for direct and reflected PD pulses to non-linear systems of sphere functions (triangulation).

The important basis of any arrival-time-based location process is the correct determination of the arrival time of the pulses, synonymous with determining the true beginning of the transient PD pulse (or a characteristic signal part unaffected when propagating through the test object). Both, manual time determination (performed by an experienced analyst) or automatic time determination with signal processing techniques are employed. Depending on the apparatus being investigated, a second technique employed in particular when using acoustic methods is signal de-noising, which may include signal filtering, signal mean value considerations (averaging) or wavelet-based de-noising approaches.

6.2 Electromagnetic methods

Propagation velocities of electromagnetic PD pulses are much higher compared to acoustic PD pulses. Hence measuring system requirements concerning resolution and accuracy of arrival time difference are higher for methods using arrival times of electromagnetic signals. The overall bandwidth of the measuring system (including sensing elements) affects the achievable overall maximum spatial location resolution, and depending on application, usually broader spectrum parts in the VHF or UHF range are required.

Depending on signal propagation characteristics in the apparatus tested, special attention is needed for assuring correctness of the mathematical models used, e.g. assuming straight propagation paths for scattered or diffracted UHF signals without correcting measured arrival times can give erroneous location results.

6.3 Acoustic methods

All-acoustic PD location can be performed signal-based and/or signal arrival-time based approaches. Depending on the high voltage apparatus, measurements are furthermore subdivided into single or multi-channel measurements.

The key task in arrival-time-based PD location is to provide a sufficient number of acoustic signals simultaneously recorded in order to solve the respective observation equations, thus allowing the PD location to be estimated.

As all-acoustic PD measurements might suffer from reduced detection sensitivity for weak or deeply hidden PD defects, acoustic-triggered averaging is applied to enhance the acoustic sensitivity. An essential requirement for successful application of this method is a repetitive acoustic PD signal measureable on at least one channel of the measurement system.

6.4 Mixed electromagnetic and acoustic methods

Acoustic PD signals are compared to electromagnetic PD signals often subject to comparatively stronger attenuation on their propagation path from source to sensing element. Acoustic measurement sensitivity can be enhanced by combining both methods, i.e. combining the acoustic and electromagnetic PD detection.

Another important advantage of coupling electromagnetic with acoustic measurements is the increased confidence of the resulting of PD combined tests. Based on the assumption that acoustic noise does not typically generate inner electromagnetic signals, nor do electromagnetic disturbances generally create acoustic signals. A stable phase relationship is generally required for the signals to be judged as PD.

Annex A
(informative)

Advantages and disadvantages of electromagnetic measurements

A.1 Advantages

Compared to the conventional PD measurement techniques as described by IEC 60270, the main advantages of VHF and UHF PD measurement methods include:

- Greater immunity to disturbances and noise, which implies that sensitive measurement of PD can be made with AC supplies that are noisy themselves, or indeed when the test object is connected to the power system. This can greatly reduce the costs of performing PD tests and increases the probability of achieving reliable results.
- VHF and UHF methods can often be used to locate the PD source, with spatial resolution that can be useful in helping to find the actual defect sites.
- Since the pulse shape and associated frequencies are preserved with wideband VHF/UHF detectors it is sometimes possible to determine the nature of the PD source with the VHF/UHF methods.
- Noise suppression:
  - Higher signal-to-noise-ratio when measuring PD in the VHF/UHF range as most of the energy from electromagnetic noise in the power system tends to occur at frequencies that are below several MHz.
  - Make use of two or more sensors and distinguish relative times of arrival of the pulses at the two sensors or more sensors to separate noise from PD pulses
- The large frequency bandwidth of VHF/UHF detection methods generally resolve different frequency and time domain characteristics better hence can help to distinguish different types and/or locations of PD within apparatus.

A.2 Disadvantages

The main disadvantage of VHF/UHF methods is that it is not possible to uniquely calibrate the magnitude of the PD in terms of its apparent charge (e.g. Pico Coulombs), as discussed in 4.3.6.

Other disadvantages:

- Since UHF/VHF detection equipment necessarily operates at higher frequencies, and the required components are more costly, the test equipment as a whole is often more costly than conventional PD detection systems.
- To achieve the advantage of noise separation and/or suppression for on-line and on-site PD testing, the sensors and their physical arrangement tends to apply for only one type of high voltage apparatus. That is sensors intended for GIS PD detection can often not be applied to measure PD in transformers or stator windings. Thus VHF/UHF systems tend to be more application specific in application.

Annex B
(informative)

Advantages and disadvantages of acoustic PD measurements

B.1 Advantages

Acoustic measurements on HV equipment are performed predominantly to detect, recognize and locate PD sources

Advantages:

- Low cost equipment (acoustic sensor plus the PD acquisition unit).
- Relatively easy to perform.
- The method is non-invasive: sensors are placed on the external surface of the enclosure during normal operation of the equipment.
- Immunity to electromagnetic noise in the substation: typically acoustic emission sensors working in ultrasonic frequency ranges are used.
- Sensitivity can be increased by combining acoustic measurements with electrical PD measurements (conventional and/or UHF method).
- The performance check of the acoustic system on site is easy to perform.

B.2 Disadvantages

Disadvantages:

- Depending on the path between the PD source and sensor, comparatively high attenuation factors can increase the time needed for on-site measurements.
- Lower sensitivity for PD source location in power transformers in the field.
- Calibration of the acoustic signal with respect to IEC 60270 is not possible.

Annex C
(informative)

Application-specific aspects

C.1 Gas insulated switchgear (GIS)

In gas-insulated switchgear, the defects which can occur and affect the dielectric performance of the equipment fall into several main categories:

a) assembly errors;
b) introduction of conductive contaminants, e.g. metallic particles;
c) poor or loose electrical and mechanical contact between conducting parts, e.g. field electrodes and shields, resulting in components at floating potentials;
d) fixed defects such as metallic protrusions on the high voltage conductor and particles attached to solid insulator (spacer) surfaces;
e) insulator defects including manufacturing defects;
f) surface tracking caused e.g. by flashovers during HV testing;
g) contamination which affect the quality of the SF_6 gas (by-products, moisture content, erroneous gas filling etc.).

Partial discharges in GIS are caused by defects of the insulating system. It has been shown that the discharge currents of PD sources in SF_6 gas exhibit have rise times that can be less than one hundred picoseconds. The defects, e.g. free moving metallic particles (the most frequent defect type) or fixed defects, cause electromagnetic transients with frequency content well above 2 GHz. The resulting signals propagate within the coaxial busbars of a GIS not only in the basic mode (TEM_{00}), but also in many higher order modes (TE_{mn}, TM_{mn}). Reflections occur at the numerous discontinuities inherently present in the internal construction which lead to the formation of multiple standing waves and resonances at varying frequencies. In addition, there are coupling effects between modes, which also influence the spatial variation in field intensity. Due to the finite conductivity of the metallic conductors and losses at dielectric boundaries and surfaces (e.g. insulators, partitions) and discontinuities (e.g. T-junctions, etc), signal propagation is affected by e.g. damping and dispersion. Signal attenuation is frequency dependent and occurs mainly at the discontinuities. The result is a complex mixture of electromagnetic wave resonances within each compartment.

In addition to the conventional method according to IEC 60270, VHF, UHF and acoustic methods are used for PD measurements in GIS.

C.2 VHF and UHF methods

The UHF signals in the UHF frequency range are typically detected by means of internal couplers, which are usually of similar design to capacitive couplers. When these are not available, it is possible to use external couplers on windows or the exposed (unshielded) edges of insulator barriers. As consequence of UHF signal attenuation, many couplers have to be installed in an extended GIS. A typical rule of thumb for the average loss of signal strength is approximately 2 dB/m. This leads to the need for couplers to be mounted at intervals of approximately 20 m along e.g. straight bus sections or feeders. Within the GIS core, the various components such as circuit breakers, disconnecting and earthing switches, current and voltage measuring transformers, and other devices, typically lead to higher values of signal attenuation when compared to straight sections of bus. The signal-to-noise ratio and therefore the sensitivity of the UHF measuring device is improved by using suitable couplers, amplifiers and filters. The UHF method has proved to be at least as sensitive in detecting defects as the conventional method according to IEC 60270, and this is mainly due to the low external noise level. Tests in laboratories and on site have shown that small critical defects- and even non-critical defects- may be detected. There is a poor correlation, however, between the acquired UHF-signal level and the apparent charge recorded by the conventional PD measuring method according to IEC 60270. An accurate location of the defect may be obtained e.g. by using a wide-band digital storage oscilloscope to measure the difference in arrival times for signals arriving at adjacent couplers. When the distance between the couplers has been measured, the defect location can be obtained by a simple calculation.

The VHF methods are different from the UHF method but there are at least some similarities. The most frequent application of the VHF methods is a broad band measurement in the range from 40 MHz to about 300 MHz. At these frequencies the TEM_{00} mode of propagation in GIS is dominant as 30 MHz is usually below the cut-off frequency of any higher order modes. Using such a technique a PD measurement is proportional to the apparent charge but only for a given location of a PD source and PD sensor. The VHF signal is taken by internal sensors i.e. metallic plate acting as an electric field sensor, however a smaller number of sensors is required compared to the UHF method. The PD measurements in the VHF range offer a better signal to noise ratio than the conventional method according to IEC 60270 but are still often influenced by external disturbance signals. As for the location of PD sources, the VHF methods provide the same advantages as the UHF methods by considering time domain signals and calculating transit times and distances for measurements on different couplers.

C.3 Acoustic methods

Acoustic signals (mechanical waves) are emitted from defects in a GIS by two primary mechanisms:

- moving particles excite a mechanical wave in the enclosure;
- PD from fixed defects create a pressure wave in the gas which transfers to the enclosure.

The resulting signal will depend on the source and on the propagation path. Several acoustic modes of propagation may exist in the enclosure. However, for the frequency ranges normally used (i.e. <150 kHz) and or normal enclosure materials and thicknesses, it is mainly the 0-th order anti-symmetric (bending) wave that needs to be considered. Because the enclosures are normally made of aluminum or steel, signal attenuation is quite small. However, the signals lose energy when they traverse boundaries between compartments, by e.g. attenuation in the insulator flange and also some of the signal is reflected.

Acoustic signals can be picked up by means of externally mounted sensors. Normally, either accelerometers or acoustic emission sensors are used. Accelerometers produce an output signal proportional to the acceleration (in the direction perpendicular to the base of the sensor) of the surface they are mounted on. The pass band is flat up to the upper limiting frequency.

Acoustic emission (AE) sensors produce an output signal proportional to the velocity (in the direction perpendicular to the base of the sensor) of the surface they are mounted on. The AE-sensors operate in resonance. International standards exist for calibrating acoustic sensors (e.g., for AE sensors; ASTM E976, ASTM E1106). Calibration of AE sensors has been the subject of particular attention. While such standards are useful for specification and control of sensors from a supplier, they are not relevant when assessing the feasibility of using the sensors on GIS. Defect identification and location is possible with this method.

The signals from a bouncing particle is broadband (i.e. >1 MHz) and has a high amplitude compared with signals emitted from pre-discharges at fixed defects, e.g. protrusions. With the temporal resolution of a normal instrument, each and every single impact between a particle and the enclosure can be distinguished as a separate event. The reflections from flanges appear as "echoes" in the signal. The particle type signal will be spatially attenuated as it moves away from the point source. Attenuation of the signal amplitude varies inversely with the square root of the distance from the source to the sensor, until the wave front embraces the enclosure where after the attenuation becomes negligible. The acoustic sensitivity to bouncing particles is usually much higher than the sensitivity of any other diagnostic method, provided the sensor is mounted on the same compartment (i.e. between flanges) containing the particle. The method has some problems with the detection of discharges from particles located at the surface inside conical spacers. Due to the high attenuation of acoustic waves in cast epoxy, the method is not very sensitive for detection of defects within the epoxy (e.g. voids).

Pre-discharges type signals from protrusions are the result of pressure waves caused by rapid local heating of the gas at the pre-discharge site. The signal will be very wideband close to the source, but because the gas acts as a low pass filter, the high frequencies are attenuated as the signal propagates away from the source towards the enclosure. Normally, detected signals from pre-discharge sources are limited to the frequency range below 100 kHz, but a source located on the enclosure will have wider frequency content. Acoustic coupling from a pressure wave in the gas to the enclosure depends mainly on the gas pressure and the angle of incidence. Acoustic instruments are not able to resolve every single gas discharge because of the insufficient time resolution of the acoustic technique; the sensors are too slow to differentiate between individual discharges. The time constants of the acoustic sensors currently in use, together with the mechanical ringing of the enclosure lead to pulse overlap. For a pre-discharge type signal, the shape of the signal is complex. The detected signal level will be a mix of backward and forward travelling waves on the enclosure resulting in a continuous signal with 50/60 Hz and/or 100/120 Hz envelope. The final peak signal level will depend on the length of the enclosure and how often there is coincidence and interference between the backward and forward travelling waves at the sensor location. The signal level is found to be fairly constant within the same section/compartment, but then it typically drops by some 8 dB once a flange (insulator) is crossed.

The signal-to-noise ratio depends on the type of sensor and the signal conditioning used. The acoustic method is very immune to electromagnetic noise in the substation. Bouncing particles create very strong signals and particles in the millimeter range producing apparent discharges in the 5 pC range are detected with a high signal to noise ratio when an appropriate sensor is used. Sensitivity decreases with distance because the acoustic signals are absorbed and attenuated as they propagate in the GIS.

C.4 Sensitivity verification of electromagnetic and acoustic measurements on GIS

C.4.1 General

With respect to the real charge, calibration of the PD measurements is not possible. However, a useful verification of the detection sensitivity can be performed for electromagnetic (UHF) and acoustic method. In both cases, the UHF and the acoustic method, the same technical principles are applied for the sensitivity verification.

C.4.2 Sensitivity verification of UHF measurements

Sensitivity verification of the UHF system ensures that GIS critical defects causing an apparent charge of 5 pC or more (when measured according to IEC 60270) can be detected by the UHF system. The procedure shall be performed in two steps.

In the first step, at the manufacturer's factory, the tests should be performed on a straight section of bus bar containing two closely located couplers connected to a coupling capacitor and calibrated per IEC 60270. A defect of critical size (free metallic particle and/or fixed protrusion on the HV conductor) shall be placed at the position of the first coupler and the bus bar shall be energized; the combination of defect and voltage level shall be adjusted such that measured apparent charge of this actual PD source is 5 pC. The UHF signal corresponding to this 5 pC apparent charge shall then be measured. Then a pulse shall be injected at the first coupler whose risetime is sufficiently short so as to produce an output spectrum equivalent to that measured from the actual 5 pC PD source, and its amplitude adjusted such that this pulsed signal matches the actual PD signal as closely as possible. The amplitude of this artificial pulse shall be recorded to be used later in the second step of the sensitivity verification.

In the second step, following on-site assembly of the GIS, the location of the couplers and proper functionality of the PD measurement system shall be verified to show that a defect having an “apparent charge” of 5 pC anywhere in the GIS is able to be detected by the UHF system. The artificial pulse obtained from the from the factory test described in the previous paragraph shall be injected at all sensors one by one, and the UHF signal shall be measured at the adjacent sensors, thus demonstrating that the UHF system has sufficient sensitivity to detect discharges of 5pC throughout the GIS.

C.4.3 Sensitivity verification of acoustic measurement

Similarly to the UHF method described in C.4.2, the sensitivity verification for acoustic measurements is intended to verify proper functionality of the measuring equipment and is also performed in a two-step procedure:

In the first step, laboratory tests are first performed to determine the frequency spectrum and signals levels from the real defect. The acoustic signal level corresponding to an apparent discharge level of 5 pC from an actual PD source as calibrated and measured per IEC 60270 is recorded with the sensor and instrument to be used. Furthermore, the frequency spectrum of the detected signal should be measured. Next, the signal from an artificial acoustic signal emitter is recorded by the acoustic measuring device. The signal can be produced by an acoustic sensor (piezo-crystal) used in reverse method (i.e. pulsed by a step voltage). When the frequency spectrum as well as the amplitude from the artificial source are established in such way that they are as similar as possible to the signal from the real PD defect, this artificial signal can then be used as a reference for the sensitivity verification. For the piezo-crystal this may be achieved by using a well-chosen sensor pulsed with a step voltage whose amplitude and rise time are set appropriately.

For the second step on-site, the sensitivity and the integrity of the measuring equipment is verified using the artificial acoustic signal source obtained from the laboratory test described in C.4.2. The enclosure shall be excited in the same way as in the laboratory, and measuring system shall be the same as that employed during the laboratory test.

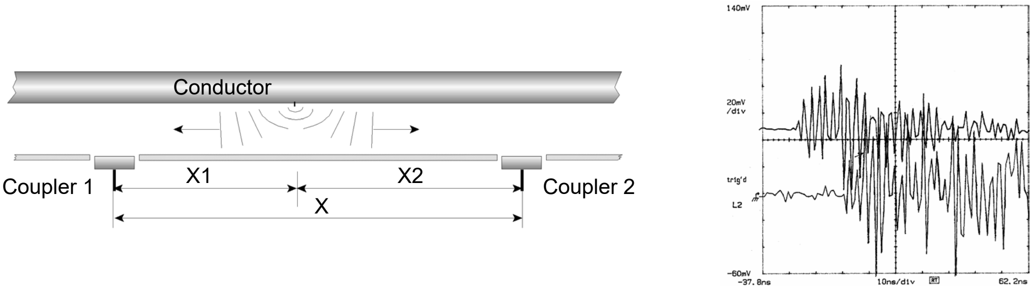
NOTE For acoustic measurements typically a 3 dB variation in sensitivity may occur simply due to removing and re-fixing the sensor. Also the acoustic waves are highly dispersive. Therefore such measurements will only be suitable for verification and not for calibration.

C.4.4 Location of PD sources inside GIS

- The dielectric failure probability is strongly dependent on the type of the defect and its location inside the GIS.
- Different procedures and methods can be used based on practical and physical background. Electrical time-of-flight measurements, typical for UHF method but also applicable for acoustic measurement, is the most frequently used method in the field.
- Methods based on time delay between different propagating modes and directional couplers, have shown to be unpractical.
- In general differentiation between time domain or frequency domain methods.

C.4.5 Time-of-flight measurements with the UHF method

- The very fast electric pulses emitted by a PD source propagates in all directions along the GIS duct (Figure C.1). It arrives at the internal couplers located on either sides of the PD source. By the time-of-flight technique the time difference between the wave fronts arriving at two couplers can indicate the location of the PD source. The time differences observed are typically in the range of tens of nanoseconds (ns), so the measurements shall be performed with a digital oscilloscope having sufficiently high sampling rate and input bandwidth. With this technique, the discharge source can be located within tens of centimeters on site.



IEC

Figure C.1 – Defect location by time-of-flight measurement

The distance between coupler 1 and the PD source can be calculated as

$$X_1 = \frac{X-(X_2-X_1)}{2} = \frac{X-\upsilon_{\mathrm{c}}\Delta t}{2} \tag{C.1}$$

where Δt is the difference in the arrival time of the signal at couplers 2 and 1 and υ_{c} is the propagation velocity of the signal: (30 cm/ns). Variations in propagation path parameters shall be taken into account; for example, in cases where e.g. an insulator of permittivity ε_{r} is traversed by the electromagnetic wave, the propagation velocity of the signal is decreased by a factor proportional to the $\sqrt{\varepsilon_{\mathrm{r}}}$ for the distance given by the thickness of the insulator.

C.4.6 Signal reduction analysis

Because of attenuation, dispersion, and resonance phenomena, the electric waves attenuate as they propagate through the GIS. If the influence of different GIS components for signal attenuation is accurately known, this can be applied to determine the PD location. Typical values for UHF signal attenuation are 2 dB/m in straight bus duct, and 1 dB to 5 dB per spacer. As the results of these assumptions are not very accurate, this method can only be used in special cases.

C.4.7 Acoustic location methods

- Time-of-flight measurements: two sensors are used and the time of arrival of the signal coming from the sensors is observed on the oscilloscope. If the source is outside the sensor pair, the signal will come from the side it arrives at first. If the source is located between the sensors the difference in arrival time is less than the time of flight between the sensors.

  NOTE The speed of sound in an enclosure is frequency dependent.

- Searching for highest amplitude: using only one sensor, one can simply look for changes in signal amplitude; the signal will typically be stronger when the sensor is placed closer to the PD source. The signal will drop off significantly when crossing to the next compartment (e.g. across an insulator or flange). It should be noted that the amplitude of the acoustic signal will decay inversely proportional to the square root of the distance from the source, as the sensor moves away from the source. The amplitude of the signal generated by moving particles varies in time, so that it is recommend that repetitive measurements are made in order to acquire the maximum amplitude value. Observation of the signal rise time: acoustic signal propagation in an enclosure is highly dispersive. The propagation velocity of the bending wave, which is the most significant wave component, increases from below 1 000 m/s to about 3 000 m/s in a frequency range between 10 and 100 kHz. Also, in the gas, the absorption increases with frequency. The consequence of these effects is that the signal front, which exhibits a very fast rise time close to the source, exhibits a progressively slower rise time as a function of distance from the source, in orther words, the signal is smeared out as it propagates away from the discharge site. Therefore, the sharper the front the closer the distance to the source.

- An even more accurate measurement can be made if the acoustic system is triggered by an electric signal picked up using e.g. a UHF coupler.
  - Sensitive to most common GIS PD defects; sensitivity to detect free moving particle is much higher than the sensitivity of any other diagnostic method provided the sensor is mounted on the same compartment (i.e. between flanges/insulators) containing the particles.
  - In the case of free metallic particles in GIS, an estimation of the criticality of the particle (its jump height, mass and length) can be performed.
  - PD source location in GIS in service and in power transformers in lab is more efficient with this method.

C.5 Rotating machines

PD occurs for many reasons in stator windings rated 3,3 kV and above. The insulation in most modern stator windings are made from layers of mica paper tape bonded together with an epoxy or polyester resin. PD can occur within voids in the main groundwall insulation due to

- poor impregnation during manufacturing,
- thermal aging which causes the resin to degrade (producing gas),
- machine load cycling that causes shear stresses within the insulation.

In addition, PD can occur on the surface of stator bars and coils due to

- loose bars or coils in the stator core,
- poorly manufactured electric stress relief coatings,
- bars or coils that are too close together outside of the stator core.

Unlike most other types of equipment, stator windings rated 3,3 kV and higher will almost always exhibit continuous, low level PD during operation, owing to the presence of ‘micro voids’ which are a normal by-product of the manufacturing processes. The winding insulation is designed to withstand this low level PD and thus does not pose a risk to long service life due to the presence of mica. However, experience shows that if the PD levels are “high”, or the PD increases over several years, then repairs or winding replacement is prudent.

PD pulses in stator windings produce thousands of pulses per second due the large number of PD sites that are typically present in a stator. The PD pulses have risetimes in the few nanoseconds range. As described in IEC TS 60034-27, these current pulses travel through a well-defined surge impedance in the stator slot, and a complex inductive-capacitive network in the stator end-windings. Thus a PD pulse excites many resonance modes, and the transmission of the PD current from the PD site to the machine terminals where PD is often measured, is very complicated. Attenuation and dispersion of the PD current pulse as it propagates through the winding is greatly dependent on many factors such as end-winding length, capacitance between the end-windings, the resistivity of the slot conductive coating, winding connections, etc.

Most off-line PD tests in stator windings are done according to IEC TS 60034-27 in the low frequency range to minimize PD pulse attenuation through the winding. Most on-line PD testing of stator windings is done in the VHF frequency range or above, to reduce the risk of false indications due to electrical interference (see IEC TS 60034-27-2). In rotating machines, acoustic measurement methods are sometimes used to locate surface PD sites within the stator windings using 40 kHz directional microphones.

Concerning electromagnetic sensors in rotating machine stator windings, capacitive sensors are the most common VHF sensors. Typically they are used in the 30 MHz to 300 MHz range, and are installed on the high voltage terminals of the machine. In many cases, two capacitive sensors per phase are used to determine from what direction a pulse is originating. In this way, stator winding PD can be distinguished from noise on the basis of relative time of pulse arrival at the two sensors. In addition, noise occurring some distance from the machine terminals, or that radiates from the rotor winding to the stator winding, has a longer pulse rise time (lower frequency content) than PD that is near to the PD sensor. Thus measurement in the VHF range permits noise discrimination based on time of pulse arrival as well as pulse shape.

Another VHF sensor sometimes used in rotating machines is a directional electromagnetic coupler, known as a stator slot coupler. It is installed in the same stator slot as bars operating at high voltage (and thus most prone to PD). PD in the same slot as the coupler is detected as a non-oscillatory pulse with a duration less than 6 ns. In contrast, noise or PD from outside of the slot is detected as an oscillatory pulse with a width > 8 ns. Thus this type of PD sensor has very high noise immunity, but can only reliably detect PD in the slot in which it is installed.

A performance check is usually done by injecting a short duration pulse (<10 ns wide) into the machine terminals. It is best to use a pulse generator with an internal impedance of less than a few ohms, and make sure all signal and earthing leads are <50 cm in length. The detected magnitude should be recorded on an oscilloscope. The detected pulse magnitude should be approximately the same for all PD sensors on the stator winding. A sensitivity check is usually not possible for testing of complete stator windings. This is because the inductive-capacitive and distributed impedance nature of the winding leads to a complex impedance vs. frequency response, making calibration into pC difficult and highly dependent on the winding characteristics and the PD detector frequency range (see IEC TS 60034-27).

C.6 Transformers

C.6.1 Physical background of high frequency and acoustic PD phenomena on transformers

PD in oil appear, in addition to the measurable electrical pulses, as source of acoustic waves in the ultra-sonic range (20 KHz to 1 MHz) and electromagnetic waves up to the UHF range (0,3 GHz to 3 GHz). Especially for onsite/online PD measurements, acoustic or electromagnetic measurements are possible, helpful and advantageous. In Figure C.2 the underlying physical principle of the detection processes considered in this work (although certain further aspects are examined) are roughly illustrated.

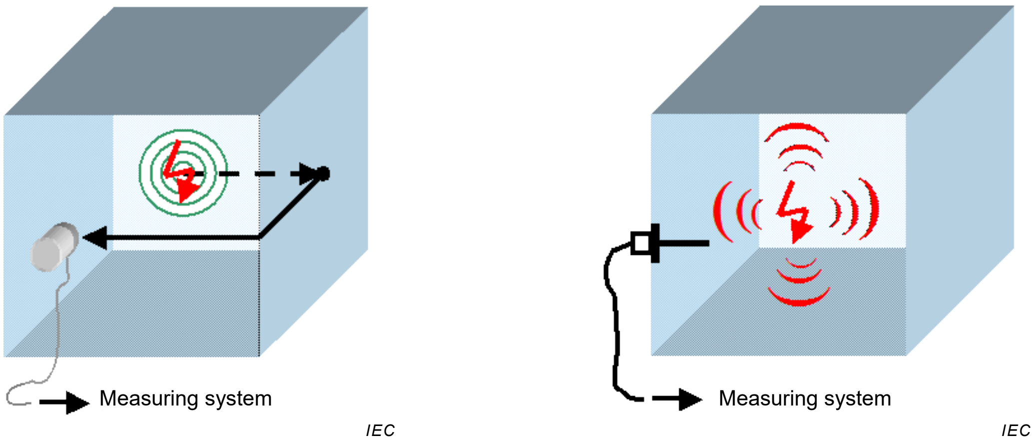


Figure C.2a – Acoustic case

Figure C.2b – Electromagnetic case

Key

ϟ PD (partial discharge)

◎ Sound field (acoustic waves)

⊐ Piezoelectric sensor

(((Electromagnetic waves

⊏— Example UHF sensor "monopole"

Figure C.2 – Illustration of the physical principle of acoustic and electromagnetic PD detection in an oil/paper insulated transformer

C.6.2 UHF PD signals in transformers

In the UHF case, the electromagnetic waves emitted from the PD may reach – after possibly several reflections inside the tank – a sensor applied, in the easiest case, through a drain valve. Working with properly shielded equipment on transformers results in an almost perfectly closed Faraday cage (excluding the dielectric openings of the bushings). Hence external disturbances are suppressed effectively. The propagation velocity of the UHF waves is, depending on the resulting ε_r, estimated to about $2/3 \times c_0$ or 2×10^8 m/s (c_0 denoting the speed of light). A reasonable frequency range of investigation might be limited 200 MHz to 2 GHz.

C.6.3 Acoustic PD signals in transformers

Acoustic PD signals are radiated as sound field which ideally propagates as a spherical pressure (longitudinal) wave until reaching the transformer housing (Figure C.2, dashed line) where more complicated modes and propagations paths can be initiated (solid line, which demonstrates a possible so-called structure-borne path e.g. for sensors not directly mounted normal to the PD source).

Insulation materials (e.g. solid insulation parts or oil) basically feature a low-pass character and the acoustic attenuation increases with good approximation proportional to the square of the frequency f^2. Practically usable frequency ranges for acoustic PD measurements has an upper limit defined by undue attenuation of material and a lower limit mainly marked out by disturbances as e.g. the so-called core-noise.

The used frequency range of piezoelectric sensors mounted on the outside of the transformer housing lies within 10 kHz to 300 kHz. The sound velocity in oil for operational temperatures between 50 °C and 80 °C vary from around 1240 m/s to 1 300 m/s.

C.6.4 Spatial location of PD sources in liquid-insulated transformers/reactors

PD location on transformers is grouped into two major tasks. First evidence of PD (detection process) is to be provided as sensitive as possible and to distinguish it from any potential disturbances at the same time. Secondly the determination of the failure origin (location of the PD) has to be performed.

Mostly measured signal propagation times are used to calculate the origin of signals. This classically often was referred to as triangulation (Figure C.3).

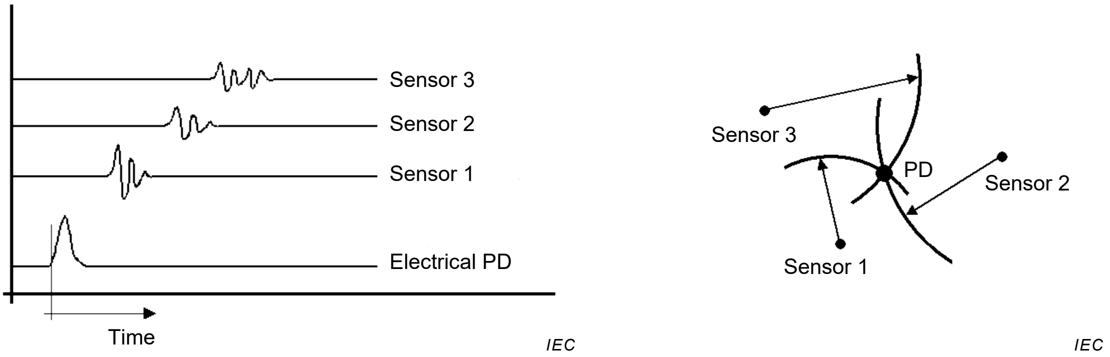


Figure C.3a – Electric PD signal and three acoustic signals

Figure C.3b – Triangulation

Figure C.3 – Classical arrival time based PD location for transformers/reactors with a combination of the electric and acoustic PD signals

Within transformers/reactors PD can be modelled as a point source radiating an acoustic and electromagnetic wave in a homogenous medium (using e.g. an average sound velocity). The appropriate non-linear observation equations are in the simplest case characterized by sphere functions around the acoustic sensors which intersect at the PD origin (Figure C.2b). This requires a signal defining the instant the PD occurs and corresponds mathematically to an absolute time measurement.

Three main variants of arrival-time-based geometric PD location can be distinguished:

a) all-acoustic PD location using only acoustic PD signals;

b) mixed electro-/electromagnetic-acoustic PD location using acoustic PD signals in combination with either electromagnetic or electric PD signals;

c) all-electromagnetic PD location using solely multiple electromagnetic PD signals from various on the transformer mounted UHF sensors.

C.7 Cable/accessories

The quality of production of extruded cables is checked by routine tests at the manufacturer's plant according to relevant standards. Installation of accessories on site has an additional risk of introducing faults. Small particles, dust, and moisture droplets etc. might lead to defects in electrically critical locations of the accessories, possibly leading to a reduced lifetime of the cable system or to failures. With suitable sensors placed directly at the accessories this information can be derived by measuring of partial discharge current pulses during the after installation dielectric tests and later, during operating of the equipment.

The advantages of the PD coupling directly at the accessories, as opposed to conventional PD coupling at the end of the cable, become more visible with increasing length of the cable systems. PD pulses are significantly attenuated when travelling along the cable. Fast PD pulses have the wave shape of few nanoseconds wave tail and consequently a frequency spectrum up to GHz range. With increasing cable length, the cable acts as a low pass filter with decreasing corner frequency. The higher the integration frequency range, the larger will be attenuation of the measured apparent impulse charge. The large attenuation of high frequency components makes the surge front smoother. For example, with a frequency band detector over 50 MHz only about 10 % of initial spectral energy of the PD pulse can be detected after travelling 500 m along a 230 kV cable. Therefore for long cables (> 500 m), the detected frequency should be lower to achieve better measurements accuracy and cover a longer cable length. In the cases of short cables or when only local areas are monitored, a higher frequency may be used to improve the measurement sensitivity and achieve better noise reduction.

The fact that the attenuation of high-frequency signals get stronger with increasing cable length is the main reason that meaningful PD measurements and PD location at the end of extruded cable systems are limited to approx. 2 km cable length. When PD coupling is performed using sensors directly at the cable accessories the attenuation of high-frequency signals leads to the desirable effect of noise reduction. Independently of the selected sensors, PD measurements should be carried out simultaneously at all cable accessories to recognize all PD activity as early as possible. Synchronous PD measurements on all accessories of a cable system are possible by using optical fibers for communication and synchronization of the distributed measuring system

Different kinds of PD sensors are used to detect PD directly at the accessories. They are based on capacitive e.g. coaxial foil electrodes, inductive (e.g. Rogowski coil, ferrite HF transformers) or electromagnetic field coupling (e.g. directional coupler sensors DCS). In order to maximize the signal-to-noise-ratio, these sensors are designed for HF or UHF detection.

The capacitive PD sensor is an electric field sensor and can easily be designed as an integral part of the accessory itself. In general, constructive elements of the accessory like stress cone electrodes can be advantageously used as a sensor, whereas the high-voltage functions of the configuration are not affected, especially in case of fast transient overvoltages. The capacitive current is typically shunted via a section of the outer semiconducting layer of the power cable, resulting in 1st order high-pass characteristic. The upper cut-off frequency of a typical capacitive sensor is at about 10 MHz and usually each joint will have only one capacitive sensor so time-of-arrival measurements for exact localization of a PD defect inside the joint become impossible. Localization not only requires a second sensor but also a sufficient measuring frequency bandwidth to achieve high accuracy.

To enable precise localization of accessory-internal PD defects, dual-sensor UHF PD detection is required. High-frequency pulses travelling along a cable are strongly attenuated within the operating frequency range of a capacitive sensor so that a differentiation of the PD origin can be reliably performed by evaluating the decrease of the pulse amplitude from the PD source to the point of measurement as well as by observing the pulse deformation. In this manner, external disturbances (e.g. corona) can accurately differentiated from PD signals caused by a defective joint by using the measurement set-up itself as signal filter.

When applying synchronous PD detection for distributed PD sensors, accurate time-of-arrival measurement enables determination of pulse propagation direction and therefore PD pulse origins can be reliably differentiated.

If only one capacitive sensor is installed in a joint, on site calibration is not possible. Since capacitive sensors are integrated components of cable accessories, retrofitting of capacitive sensors is almost always impossible.

Inductive PD sensors are sensitive to the magnetic field components. They become advantageous if built-in PD sensors are not available. In this case, inductive sensors mounted on screen or cross-bonding (CB) links can provide an easy access for sensitive PD detection at cable accessories. CB link boxes are also accessible for direct buried systems.

A directional coupler sensor (DCS) is a passive RF-device, which couples energy to different output ports, depending on the pulse travelling direction. The directional coupler principle can be applied for PD detection on high voltage cables using a specially designed sensing electrode with two coaxial outputs. The sensing electrode is completely shielded and therefore insensitive to external interferences.

The directional coupler is characterized by two basic properties, the coupling attenuation, which corresponds to the sensitivity of the sensor and the directivity, which determines the ability to distinguish between different pulse travelling directions by the magnitude relations of both outputs of the directional coupler sensor.

Logical combination of the different coupling configurations can clearly classify the origin of the signal and thus differentiate external disturbances from PD from the accessory. In order to achieve a high sensitivity as well as a high directivity, the sensor is usually adjusted to the properties of the high voltage cable and mounted directly on outer semiconducting layer.

Though directional coupler sensors show excellent intrinsic capability to distinguish between external and (accessory) internal PD, practical applications were quite rare. Compared to alternatives, DCS need specific adaptation to the cable design, especially to the UHF characteristic of the outer semiconducting layer, requiring HF specialists. The DCS signal processing (4 channels for each joint, UHF) is more costly than single-channel signal processing. Moreover, noise level detected with capacitive or inductive sensors at joints on site does not require more sophisticated (and more expensive) PD sensors. DCS works perfect for joints and GIS terminals, but not for outdoor terminals, where a second DCS could not be applied. Unfortunately, outdoor terminals show highest noise levels and so best possible discrimination between external and internal PD would be highly appreciated. When really needed, DCS would not help. Consequently, non-directional UHF sensors are applied in case of cable terminals.

A PD detection sensitivity of a few pC could also be achieved by means of UHF sensors which are adopted external to the cable accessories under operation voltage.

In the case of UHF sensor on cable termination, each of them is embedded in a post insulator located between base plate and earth. The sensors are fully enclosed in cast resin housing and thus are suitable for outdoor use, as the post insulator can withstand temperatures of up to 55 °C. At the firmly bonded end of the sheath the sensors are in parallel to the earth connection. At the open end the sensor type with internal capacitor is applied for blocking induced currents.

In general, the attenuation of the PD pulses is a function of frequency. Therefore, detecting PD in the UHF band (300 MHz to 3 000 MHz), that has only a few known discrete interferences, also has the advantage of the distance selectivity of only several meters. This can be perfectly used for the diagnosis of the concentrated equipment such as cable termination.

Due to the symmetrical configuration of power cables each PD event produces two equal current pulses. Charge magnitude of each of them amounts one half of the initial entire impulse. Both impulses travel away from the PD source in both directions. At the remote end of the cable section, which is generally open during the PD measurement, a full reflection occurs. Therefore at the near end of the cable, where the PD coupling unit is connected, not only the direct pulse but also the reflected pulse can be detected. This occurrence is used for location the PD site using the time domain reflectometry (TDR).

PD pulses are also partly reflected at joints due to small change of wave impedance depending on joint design and materials. When cross-bonding (CB) is applied on long three-phase cable systems, PD pulses can change between the phases.

Check-of-performance of the PD measuring system composed of PD acquisition units located at cable accessories and measuring PD at all device locations synchronously can be performed according to the following steps:

Step 1 – Verification of the functional readiness of the measuring system

The functional readiness of the measuring system (of all PD sensors, acquisition units and measuring channels) shall be verified. The internal test signal generator of each PD measuring unit can be used for such verification.

Step 2 – Verification of the synchronous behaviour of the PD measuring system

For this scope, the calibration pulses of appropriate magnitude shall be fed in via one cable outdoor termination. The PD units shall be connected in synchronous way. The calibration signal and its part-reflection at the next accessory shall clearly be distinguished from the background noise level from all connected units.

Step 3 – Determination of PD impulse attenuation, damping and dispersion

The following parameters shall be determined:

- PD impulse attenuation, damping and dispersion along the cable line;
- velocity of the calibration signal in the cable line;
- best frequency ranges for PD measurements at all PD units (with highest signal to noise ratio);
- PD detection path division factor for every chosen frequency range.

Step 4 – Final functional check of the measuring system at corona PD – "wire test"

If the external source of the voltage is available (e.g. during after installation test), it is recommended to perform the so called "wire test". The copper wire shall be connected to high voltage and directed to ground. The high voltage shall be applied to generate the corona discharge on the wire. The PD units shall detect the simulated phenomena and the attenuation of the signal shall be observed for the frequency ranges chosen for the measurements. The "wire test" demonstrates the functionality of all PD stations and measuring channels. The frequency dependent attenuation of corona PD signal demonstrates the selectivity of PD measurements at the individual accessories. The interference from the test setup shall not play any role.

Bibliography

IEC TS 60034-27-2, *Rotating electrical machines – Part 27-2: On-line partial discharge measurements on the stator winding insulation of rotating electrical machines*

IEC 60060-2, *High-voltage test techniques – Part 2: Measuring systems*

IEC TS 61934, *Electrical insulating materials and systems – Electrical measurement of partial discharges (PD) under short rise time and repetitive voltage impulses*

IEC 62068:2013, *Electrical insulating materials and systems – General method of evaluation of electrical endurance under repetitive voltage impulses*

ASTM E976, *Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response*

ASTM E1106, *Standard Test Method for Primary Calibration of Acoustic Emission Sensors*

CIGRE, Joint Task Force 15/33.03.05: Partial Discharge Detection System for GIS: Sensitivity Verification for the UHF Method and the Acoustic Method; Electra No. 183, April 1999

This page deliberately left blank

British Standards Institution (BSI)

BSI is the national body responsible for preparing British Standards and other standards-related publications, information and services.

BSI is incorporated by Royal Charter. British Standards and other standardization products are published by BSI Standards Limited.

About us

We bring together business, industry, government, consumers, innovators and others to shape their combined experience and expertise into standards -based solutions.

The knowledge embodied in our standards has been carefully assembled in a dependable format and refined through our open consultation process. Organizations of all sizes and across all sectors choose standards to help them achieve their goals.

Information on standards

We can provide you with the knowledge that your organization needs to succeed. Find out more about British Standards by visiting our website at bsigroup.com/standards or contacting our Customer Services team or Knowledge Centre.

Buying standards

You can buy and download PDF versions of BSI publications, including British and adopted European and international standards, through our website at bsigroup.com/shop, where hard copies can also be purchased.

If you need international and foreign standards from other Standards Development Organizations, hard copies can be ordered from our Customer Services team.

Copyright in BSI publications

All the content in BSI publications, including British Standards, is the property of and copyrighted by BSI or some person or entity that owns copyright in the information used (such as the international standardization bodies) and has formally licensed such information to BSI for commercial publication and use.

Save for the provisions below, you may not transfer, share or disseminate any portion of the standard to any other person. You may not adapt, distribute, commercially exploit, or publicly display the standard or any portion thereof in any manner whatsoever without BSI's prior written consent.

Storing and using standards

Standards purchased in soft copy format:

- A British Standard purchased in soft copy format is licensed to a sole named user for personal or internal company use only.
- The standard may be stored on more than 1 device provided that it is accessible by the sole named user only and that only 1 copy is accessed at any one time.
- A single paper copy may be printed for personal or internal company use only.

Standards purchased in hard copy format:

- A British Standard purchased in hard copy format is for personal or internal company use only.
- It may not be further reproduced – in any format – to create an additional copy. This includes scanning of the document.

If you need more than 1 copy of the document, or if you wish to share the document on an internal network, you can save money by choosing a subscription product (see 'Subscriptions').

Reproducing extracts

For permission to reproduce content from BSI publications contact the BSI Copyright & Licensing team.

Subscriptions

Our range of subscription services are designed to make using standards easier for you. For further information on our subscription products go to bsigroup.com/subscriptions.

With **British Standards Online (BSOL)** you'll have instant access to over 55,000 British and adopted European and international standards from your desktop. It's available 24/7 and is refreshed daily so you'll always be up to date.

You can keep in touch with standards developments and receive substantial discounts on the purchase price of standards, both in single copy and subscription format, by becoming a **BSI Subscribing Member**.

PLUS is an updating service exclusive to BSI Subscribing Members. You will automatically receive the latest hard copy of your standards when they're revised or replaced.

To find out more about becoming a BSI Subscribing Member and the benefits of membership, please visit bsigroup.com/shop.

With a **Multi-User Network Licence (MUNL)** you are able to host standards publications on your intranet. Licences can cover as few or as many users as you wish. With updates supplied as soon as they're available, you can be sure your documentation is current. For further information, email subscriptions@bsigroup.com.

Revisions

Our British Standards and other publications are updated by amendment or revision.

We continually improve the quality of our products and services to benefit your business. If you find an inaccuracy or ambiguity within a British Standard or other BSI publication please inform the Knowledge Centre.

Useful Contacts

Customer Services
Tel: +44 345 086 9001
Email (orders): orders@bsigroup.com
Email (enquiries): cservices@bsigroup.com

Subscriptions
Tel: +44 345 086 9001
Email: subscriptions@bsigroup.com

Knowledge Centre
Tel: +44 20 8996 7004
Email: knowledgecentre@bsigroup.com

Copyright & Licensing
Tel: +44 20 8996 7070
Email: copyright@bsigroup.com

BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK