



BSI Standards Publication

# Rotating electrical machines

Part 27: Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines

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**National foreword**

This Draft for Development is the UK implementation of CLC/TS 60034-27:2011.

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**Rotating electrical machines -  
Part 27: Off-line partial discharge measurements on the stator winding  
insulation of rotating electrical machines  
(IEC/TS 60034-27:2006)**

Machines électriques tournantes -  
Partie 27: Mesures à l'arrêt des décharges  
partielles effectuées sur le système  
d'isolation des enroulements statoriques  
des machines électriques tournantes  
(CEI/TS 60034-27:2006)

Drehende elektrische Maschinen -  
Teil 27: Off-line-Teilentladungsmessungen  
an der Statorwicklungsisololation drehender  
Maschinen  
(IEC/TS 60034-27:2006)

This Technical Specification was approved by CENELEC on 2011-01-25.

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## Foreword

The text of the Technical Specification IEC/TS 60034-27:2007, prepared by IEC TC 2, Rotating machinery, was submitted to the formal vote and was approved by CENELEC as CLC/TS 60034-27 on 2011-01-25.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN and CENELEC shall not be held responsible for identifying any or all such patent rights.

The following date was fixed:

- latest date by which the existence of the CLC/TS  
has to be announced at national level (doa) 2011-07-25

Annex ZA has been added by CENELEC.

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## Endorsement notice

The text of the Technical Specification IEC/TS 60034-27:2006 was approved by CENELEC as a Technical Specification without any modification.

## **Annex ZA** (normative)

### **Normative references to international publications with their corresponding European publications**

The following referenced documents are indispensable for the application 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.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

| <u>Publication</u> | <u>Year</u> | <u>Title</u>                                                                           | <u>EN/HD</u> | <u>Year</u> |
|--------------------|-------------|----------------------------------------------------------------------------------------|--------------|-------------|
| IEC 60060-1        | -           | High-voltage test techniques -<br>Part 1: General definitions and test<br>requirements | EN 60060-1   | -           |
| IEC 60060-2        | -           | High-voltage test techniques -<br>Part 2: Measuring systems                            | EN 60060-2   | -           |
| IEC 60270          | 2000        | High-voltage test techniques - Partial<br>discharge measurements                       | EN 60270     | 2001        |

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## INTRODUCTION

For many years, the measurement of partial discharges (PD) has been employed as a sensitive means of assessing the quality of new insulation as well as a means of detecting localized sources of PD in used electrical winding insulation arising from operational stresses in service. Compared with other dielectric tests (i.e. the measurement of dissipation factor or insulation resistance) the differentiating character of partial discharge measurements allows localized weak points of the insulation system to be identified.

The PD testing of rotating machines is also used when inspecting the quality of new assembled and finished stator windings, new winding components (e.g. form-wound coils and bars, HV bushings, etc.) and fully impregnated stators.

In connection with the servicing and overhaul of rotating machines, the measurement of partial discharges can also provide information on:

- points of weakness in the insulation system;
- ageing processes;
- further measures and intervals between overhauls.

Although the PD testing of rotating machines has gained widespread acceptance, it has emerged from several studies that not only are there many different methods of measurement in existence but also the criteria and methods of analysing and finally assessing the measured data are often very different and not really comparable. Consequently, there is an urgent need to give some guidance to those users who are considering the use of PD measurements to assess the condition of their insulation systems.

Partial discharge testing of stator windings can be divided into two broad groups:

- a) off-line measurements, in which the stator winding is isolated from the power system and a separate power supply is employed to energize the winding;
- b) on-line measurements, in which the rotating machine is operating normally and connected to the power system.

Both of these approaches have advantages and disadvantages with respect to one another. A brief discussion of the merits of on-line testing, as well as the drawbacks, is provided in Annex A. However, while acknowledging the extensive world-wide use of on-line methods and their proven value to industry, this technical specification is confined to off-line techniques. This approach is considered necessary to render this specification sufficiently concise to be of use by non-specialists in the field of PD testing.

#### Limitations:

When stator windings are being tested different types of PD measuring instruments will inevitably produce different results and consequently PD measurements will only be comparable under certain conditions. Therefore, absolute limits for the windings of rotating machines, for example as acceptance criteria for production or operation, are difficult to define. This is mainly due to pulse propagation phenomena, specific difficulties with calibration and the individual frequency response characteristics of stator windings and PD measuring systems.

In addition, the degree of deterioration, and hence the risk of insulation system failure, depends on the specific type of PD source and its location within the stator winding insulation, both of which can influence the test results very significantly.

Empirical limits verified in practice can be used as a basis for evaluating test results. Furthermore, PD trend evaluation and comparisons with machines of similar design and similar insulation system measured under similar conditions, using the same measurement equipment, are recommended to ensure reliable assessment of the condition of the stator winding insulation.

Users of PD measurement should be aware that, due to the principles of the method, not all insulation-related problems in stator windings can be detected by measuring partial discharges (e.g. insulation failures involving continuous leakage currents due to conductive paths between different elements of the insulation or pulseless discharge phenomena).

For testing individual winding components, the limitations due to pulse propagation phenomena need not be considered when interpreting the results of measurements.

## ROTATING ELECTRICAL MACHINES –

### Part 27: Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines

#### 1 Scope

This part of IEC 60034 which is a technical specification provides a common basis for

- measuring techniques and instruments,
- the arrangement of test circuits,
- normalization and testing procedures,
- noise reduction,
- the documentation of test results,
- the interpretation of test results

with respect to partial discharge off-line measurements on the stator winding insulation of rotating electrical machines when tested with alternating voltages up to 400 Hz. This technical specification applies to rotating machines having bars or form wound coils with conductive slot coating. This is usually valid for machines with voltage rating of 6 kV and higher. The measurement methods described in this specification may also be applied to machines without conductive slot coating. However, results may be different and are not covered by this specification.

#### 2 Normative references

The following referenced documents are indispensable for the application 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 60060-1, *High-voltage test techniques – Part 1: General definitions and test requirements*

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

IEC 60270:2000, *High-voltage test techniques – Partial discharge measurements*

#### 3 Terms and definitions

For the purposes of this document, the general terms and definitions for partial discharge measurements given in IEC 60270 apply, together with the following.

##### 3.1

##### **off-line measurement**

measurement taken with the rotating machine at standstill, the machine being disconnected from the power system

NOTE The necessary test voltage is applied to the winding from a separate voltage source.

**3.2****on-line measurement**

measurement taken with the rotating machine in normal operation

**3.3****stress control coating**

paint or tape on the surface of the groundwall insulation that extends beyond the conductive slot portion coating in high-voltage stator bars and coils

NOTE The stress control coating reduces the electric field stress along the winding overhang to below a critical value that would initiate PD on the surface. The stress control coating overlaps the conductive slot portion coating to provide electrical contact between them.

**3.4****conductive slot coating**

conductive paint or tape layer in intimate contact with the groundwall insulation in the slot portion of the coil side, often called semiconductive coating

NOTE This coating provides good electrical contact to the stator core.

**3.5****resistance temperature detector****RTD**

a temperature detector inserted into the stator winding, usually between the top and bottom bar or embedded coil sides in a given slot

**3.6****slot discharges**

discharges that occur between the outer surface of the slot portion of a coil or bar and the grounded core laminations

**3.7****internal discharges**

discharges that occur within the insulation system

**3.8****surface discharges**

discharges that occur on the surface of the insulation or on the surface of winding components in the winding overhang or the active part of the machine winding

**3.9****pulse height distribution**

the number of pulses within a series of equally-spaced windows of pulse magnitude during a predefined measuring time

**3.10****pulse phase distribution**

the number of pulses within a series of equally-spaced windows of phase during a predefined measuring time

**3.11****partial discharge pattern**

PD distribution map of PD magnitude vs a.c. cycle phase position, for visualization of the PD behaviour during a predefined measuring time, in which specific PD parameters are used for graphical representation

**3.12****coupling device**

usually an active or passive four-terminal network that converts the input currents to output voltage signals

NOTE These signals are transmitted to the measuring instrument by a transmission system. The frequency response of the coupling device is normally chosen at least so as to efficiently prevent the test voltage frequency and its harmonics from reaching the measuring instrument.

**3.13****PD coupling unit**

a high voltage coupling capacitor of low inductance design and a low voltage coupling device in series

**3.14****largest repeatedly occurring PD magnitude**

$Q_m$

the largest magnitude recorded by a measuring system which has the pulse train response in accordance with 4.3.3 of IEC 60270, or the magnitude associated with a PD pulse repetition rate of 10 pulses per second (pps), which can be directly inferred from a pulse height distribution

**3.15****normalized quantity number**

**NQN**

normalized area under a straight line fitted to the pulse counts in each magnitude window of a pulse height analysis, in which the pulse counts are expressed as a logarithm of the pulses per second and the pulse magnitude window is a linear scale

**4 Nature of PD in rotating machines****4.1 Basics of PD**

Generally, partial discharges (PD) can develop at locations where the dielectric properties of insulating materials are inhomogeneous. At such locations, the local electrical field strength may be enhanced. Due to local electrical over-stressing this may lead to a local, partial breakdown. This partial breakdown does not result in a total breakdown of the insulation system. PD in general requires a gas volume to develop, for example in gas filled voids embedded in the insulation, adjacent to conductors or at insulation interfaces.

A partial discharge can occur when the local field strength of each inhomogeneity exceeds its breakdown field. This process may result in numerous PD pulses during one cycle of the applied voltage.

The amount of charge transferred in the discharge is closely related to the specific properties of the inhomogeneity such as the dimensions, the actual breakdown voltage and the specific dielectric properties of the materials involved, for example surface properties, kind of gas, gas pressure, etc.

Stator winding insulation systems for high voltage machines will normally have some PD activity, but are inherently resistant to partial discharges due to their inorganic mica components. However, significant PD in these machines is usually more a symptom of insulation deficiencies, like manufacturing problems or in-service deterioration, rather than being a direct cause of failure. Nevertheless, depending on the individual processes, PD in machines may also directly attack the insulation and thus influence the ageing process. The time to failure may not correlate with PD levels, but depends significantly on other factors, for example operating temperature, wedging conditions, degree of contamination, etc.

The measurement and the analysis of the specific PD behaviour can be efficiently used for quality control of new windings and winding components and for early detection of insulation deficiencies caused by thermal, electrical, ambient and mechanical ageing factors in service, which might result in an insulation fault.

## **4.2 Types of PD in rotating machines**

### **4.2.1 General**

Partial discharges may develop throughout the stator winding insulation system due to specific manufacturing technologies, manufacturing deficiencies, normal in-service ageing, or abnormal ageing. Machine design, the nature of the materials used, manufacturing methods, operating conditions, etc. can profoundly affect the quantity, location, characteristics, evolution and the significance of PD. For a given machine, the various PD sources may be identified and distinguished in many cases by their characteristic PD behaviour.

### **4.2.2 Internal discharges**

#### **4.2.2.1 Internal voids**

Although manufacturing processes are designed to minimize internal voids, inevitably there is some void content in a resin impregnated mica tape insulation system that is normally used in high voltage rotating machines. Actually, the mica in the insulation system prevents the partial discharges from developing into a complete breakdown. As long as internal voids are small and do not significantly enlarge, operational reliability is not reduced.

#### **4.2.2.2 Internal delamination**

Internal delamination within the main insulation can be caused by imperfect curing of the insulation system during manufacturing or by mechanical or thermal over-stressing during operation. Large voids may develop over a large surface resulting in discharges of relatively high energy, which may significantly attack the insulation. In particular, delamination will reduce the thermal conductivity of the insulation, which might lead to accelerated ageing or even a thermal runaway. Thus, delamination needs careful consideration when PD activity is being assessed.

#### **4.2.2.3 Delamination between conductors and insulation**

Delamination at the interface of the copper conductor and the main insulation that usually results from excessive thermal cycling is dangerous since the turn or strand insulation of the conductors can be severely damaged.

#### **4.2.3 Slot discharges**

Slot discharges in high voltage machines will develop when the conductive slot portion coating is damaged due to bar/coil movement in the slot or slot exit area, for example by a loss of wedging pressure due to settlement, erosion of the material, abrasion, chemical attack or manufacturing deficiencies. High-energy discharges will develop when serious mechanical damage is already present, which may result in additional damage to the main insulation and eventually in an insulation fault. In the early stage, slot discharges are rather vibration sparking than being classical partial discharges. This vibration sparking may also occur at low potential sites, for example close to the star point of the winding. Though the absolute time between detection of this phenomenon and final insulation failure is unknown, but could be short, reliable detection at an early stage is necessary to initiate appropriate remedial action.

#### **4.2.4 End-winding surface discharges**

Partial discharges in the end-winding area may occur at several locations with high local electric field strengths. Such discharges usually occur at interfaces between different elements of the stator winding overhang. If the stress control coating of the end-winding becomes ineffective because of poorly designed interfaces, contamination, porosity, thermal effects, etc. reliable field grading is no longer assured and surface discharges will develop, which may gradually erode the materials. This is normally a very slow failure mechanism, even though the PD behaviour might be subjected to relatively fast changes due to surface effects. In addition, PD may occur between phases, for example due to inadequate interface clearance, at elements of the overhang support system, or as phase to ground discharges on the end-winding surface.

#### **4.2.5 Conductive particles**

Conductive particles, especially small particles, for example due to contamination of the winding, may result in a strong local concentration of partial discharges. This may result in a 'pin-hole' in the insulation.

### **4.3 Pulse propagation in windings**

At its origin a partial discharge current can be characterized as a transient pulse with a rise time of only a few nanoseconds. For these short PD pulses with a high frequency spectrum, the stator windings represent objects with distributed elements in which travelling wave, complex capacitive and inductive coupling, and resonance phenomena occur. Therefore, PD pulse propagation phenomena need to be considered. Due to the attenuation, distortion, reflection and cross-coupling of travelling wave signals, the form and magnitude of the PD signal recorded at the terminals of the winding differ from those at the point where it originates. With that in mind, the following points are very important for interpreting PD measurements taken on rotating machines:

- the transmission function from the PD source to the PD sensor is unknown and depends on the specific design of the machine which determines the frequency response of the stator winding. Therefore, the energy at the source of the PD, which can be taken as a measure of the erosion of the insulation, cannot be measured directly;
- the individual high frequency transmission behaviour of a stator winding produces PD signals at the terminals that are a characteristic of the machine being tested and of the location of the PD source;
- very high frequency components of PD signals are subject to considerable attenuation when travelling through the winding and, depending on the origin of the PD, might not be detectable at the terminals of the test object

As a consequence of the above-mentioned phenomena not only the particular stator winding design but also the specific frequency response of the PD detection system, including coupling devices, will significantly influence the characteristics of the signal detected at the terminals of the winding.

## 5 Measuring techniques and instruments

### 5.1 General

In line with IEC 60270, this clause deals solely with electrical methods of measuring partial discharges because the electrical, conductive measurement of partial discharges is the most commonly used method of assessing the winding insulation of rotating machines. Non-electrical methods of measurement and localization are listed in Annex B.

Partial discharge measuring systems can be divided into subsystems: coupling device, transmission system (for example, connecting cable or optical link) and measuring instrument. In general, the transmission system does not contribute to the circuit characteristics, apart from some possible signal attenuation, and will thus not be taken into consideration.

### 5.2 Influence of frequency response of measurement system

The frequency response of the PD detection system, including the PD coupling unit, determines how much energy of the PD signal from the winding can be detected. Thus, the frequency response of the system, especially the type of coupling unit being used, has a considerable impact on the overall sensitivity of detection. Due to the different values of lower cut-off frequency, the following qualitative relationships are basically applicable when testing complete windings:

- measurement in the lower frequency range ensures good sensitivity not only for partial discharges in bars/coils close to the sensor but also for those that originate from further away in the winding. However, the lower frequency range is more subjected to noise and disturbances;
- measurement in the very high frequency range may acquire only a very small proportion of the total PD energy, which results in sensitivity to signals originating only very close to the sensor. However, this frequency range may be less susceptible to noise and disturbance.

For off-line PD testing to obtain appropriate sensitivity to PD from the whole winding it is advisable to use wide band PD measuring systems. The lower cut-off frequency should be in the range of several tens of kHz in accordance with IEC 60270.

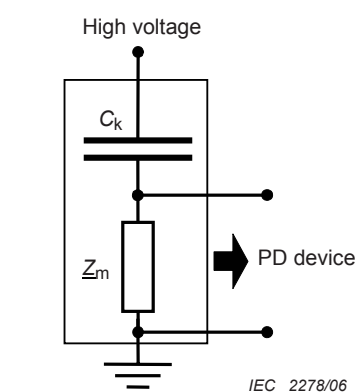
It should be noted that depending on the winding design and the measurement arrangement used, resonance phenomena that are in the frequency range of the PD measuring device may occur and therefore may also influence PD results.

### 5.3 Effects of PD coupling units

For off-line PD measurements on stator windings and PD tests on winding components capacitive coupling units are often used. These consist of a high voltage capacitor and a low voltage coupling device in series. When testing individual winding components, the coupling device may also be connected in series to the test object (see Figure 5b). The low voltage coupling device is connected to the transmission system.

The high voltage capacitor, the coupling device, the transmission system and the input impedance of the measurement system represent a high-pass filter. Therefore, increased input impedance or higher capacitance values lead to an increased sensitivity.

Figure 1 shows schematically the frequency response of an idealized PD pulse and the transfer functions of different PD coupling units with a high voltage capacitor and a resistive measuring impedance  $Z_m=R$  at the low voltage side. The marked overlap of the spectra of the PD pulse and the coupling unit, shown in Figure 1, for an RC time constant of 5 ns, determines the signal energy which can be measured. In practical cases, such systems show band pass filter characteristics due to parasitic L and C components.



time constant of PD coupling unit

for  $Z_m=R$ :  $\tau = RC$

lower cut-off frequency:

$$f_{l0} = 1/(2\pi RC)$$

#### Components

$Z_m$  measuring impedance

$C_k$  coupling capacitor

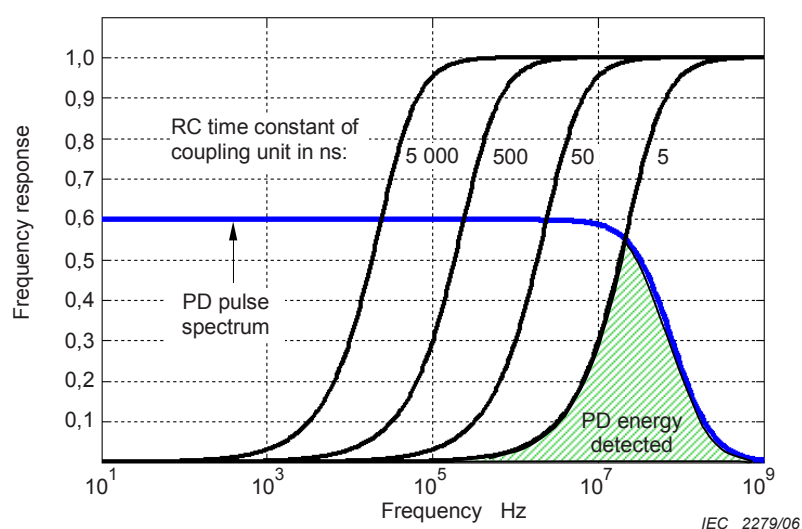


**Figure 1 – Frequency response of a PD pulse and coupling units of various time constants**

PD pulses are attenuated and dispersed especially at higher frequencies while propagating through the winding. Therefore, measurement systems with lower cut-off frequency in the lower frequency range usually provide an average good sensitivity to PD from the whole winding.

When taking measurements on individual winding components, the high voltage coupling capacitor is connected to the copper conductor. For PD measurements on complete windings, the coupling unit is connected to the terminals of the machine or inside the frame directly to the winding conductors.

The following low voltage coupling devices are typically combined with the high voltage capacitor:

- RLC filters or four-terminal networks (see IEC 60270) wherein an inductance serves to suppress the power frequency component;
- high-frequency current transformers (RF-CT) which may also serve to galvanically separate the high voltage circuitry from the measuring device.

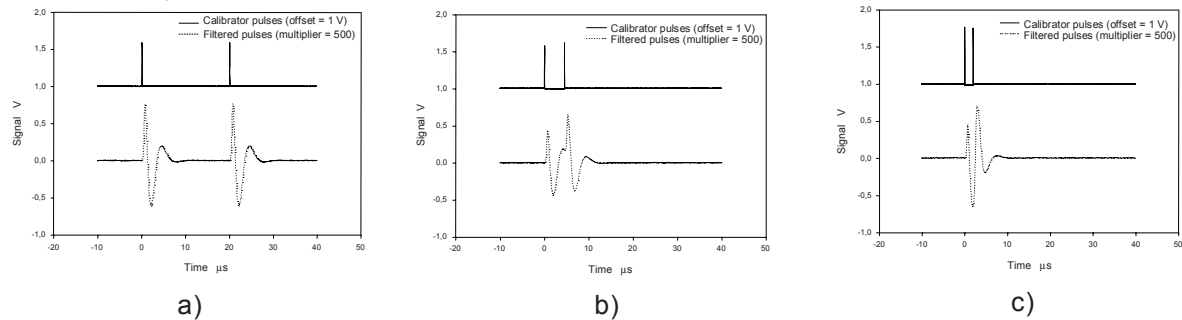
RF-CT connected with ground wires can also be used as a standalone coupling device. When using fibre optical signal transmitters, the coupling devices can also be installed on the HV side of the capacitor.

#### 5.4 Wide-band and narrow band measuring systems

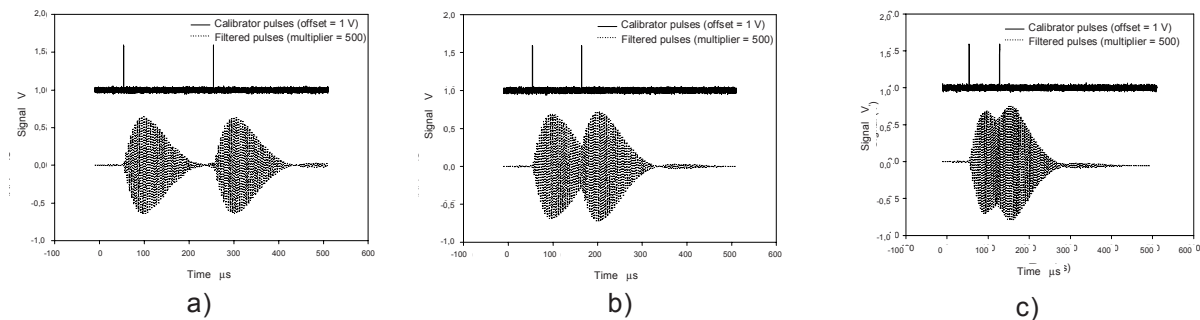
The principal difference between the various PD measuring systems is their bandwidth. The PD pulses arriving at the terminals have a frequency spectrum characterized by the transmission function of the machine winding. The measured PD signal will be affected to a greater or lesser degree depending on the bandwidth of the measuring system. Furthermore, micaceous insulation systems are characterized by a high repetition rate of PD pulses. Figure 2 shows typical pulse responses of different measuring systems. The upper trace of the oscillograms represents the input pulse, and the lower trace the pulse response of the measuring system:

- 1) wide band system: (a) low pulse repetition rate, (b) increased rate, (c) high rate leading to superposition of pulses,
- 2) narrow band system: (a) low pulse repetition rate, (b) increased rate, (c) high rate leading to superposition of pulses.

1) Wide band system:  $\Delta f$  at –3 db: 210 kHz (2nd order-filters)



2) Narrow band system:  $\Delta f$  at –3 db: 9 kHz (2nd order-filters)



IEC 2280/06

**Figure 2 – Typical pulse responses of wide band and narrow band PD systems**

(1) Wide band systems

In accordance with IEC 60270, PD measuring systems are defined as wide band if their bandwidth exceeds 100 kHz. With rotating machinery, wide-band measuring systems are typically used up to a bandwidth of approximately 1 MHz. Some systems use bandwidths of up to 500 MHz. The system bandwidth is determined by the frequency response of the coupling unit and by the signal processing in the measuring instrument.

Most of the wide band PD measuring devices conform to the requirements of IEC 60270. The lower limit frequency is set to  $\geq 10$  kHz to suppress mains frequency and its harmonics. The lower limit frequency may be variable up to a few hundred kHz to suppress external disturbances, for example commutating pulses from power semiconductors. Typical bandwidths of many measuring devices vary between 100 kHz and 1 MHz.

Some PD measuring devices use bandwidths of several 100 MHz with options to include digital oscilloscopes. The measured values of pulse amplitude are not calibrated or normalized in units of charge, in accordance with IEC 60270, but are quoted in mV. Some of these instruments are able to suppress external disturbance signals by means of differential measurements.