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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

Rotating electrical machines –

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

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ROTATING ELECTRICAL MACHINES –

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

FOREWORD

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- 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 60034-27, which is a technical specification, has been prepared by IEC technical committee 2: Rotating machinery.

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

Enquiry draft	Report on voting
2/1384/DTS	2/1395A/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.

A list of all parts of the IEC 60034 series, under the general title *Rotating electrical machines*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result 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- withdrawn,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.

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 'pinhole' 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.

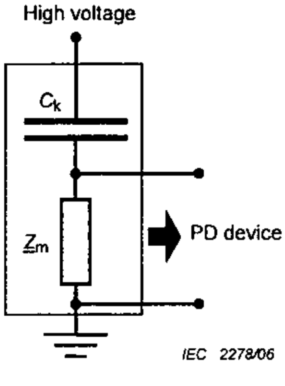
It should be noted that depending on the winding design and the measurement arrangement used, resonance phenomena that are in the frequency range of the PD measuring device may occur and therefore may also influence PD results.

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 $\underline{Z}_m=R$ 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.

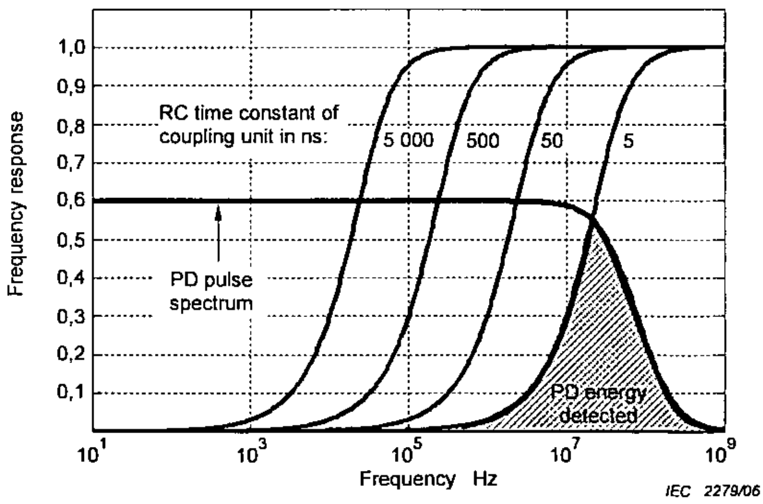


time constant of PD coupling unit

for $\underline{Z}_m=R$: $\tau = RC$

lower cut-off frequency:

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



Components

$\underline{Z}_m$ 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.

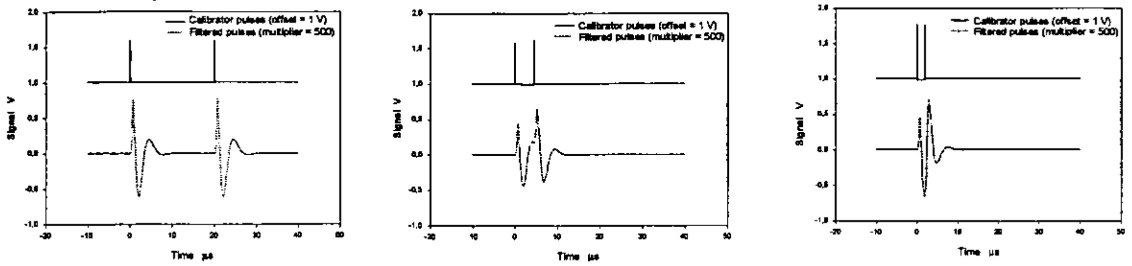
RF-CT connected with ground wires can also be used as a standalone coupling device. When using fibre optical signal transmitters, the coupling devices can also be installed on the HV side of the capacitor.

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:

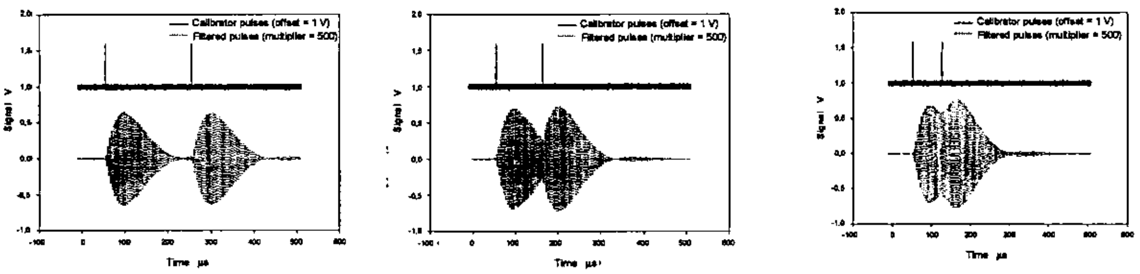
1) wide band system: (a) low pulse repetition rate, (b) increased rate, (c) high rate leading to superposition of pulses,
2) narrow band system: (a) low pulse repetition rate, (b) increased rate, (c) high rate leading to superposition of pulses.

1) Wide band system: Δ*f* at –3 db: 210 kHz (2nd order-filters)



a) b) c)

2) Narrow band system: Δ*f* at –3 db: 9 kHz (2nd order-filters)



a) b) c)

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 ≥ 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.

(2) Narrow band systems

Narrow band PD measuring devices are characterized by a small bandwidth of 9 kHz to 30 kHz with an adjustable centre frequency in a wide range of up to 1 MHz. The large number of partial discharges in mica insulation in conjunction with the long decay time of the oscillating pulses may lead to a superposition of successive discharges (see Figure 2). Thus, the readings of the individual pulse charge may be erroneous. Consequently, narrow band measuring systems are less frequently used for taking partial discharge measurements on rotating machinery.

(3) Quadratic rate based systems

The quadratic rate in accordance with IEC 60270 is expressed as $(\text{coulombs})^2$ per second and assigns greater weight to larger pulses. The centre frequency of a narrow band filter is set to several kHz, with a narrow bandwidth of several hundred Hz. The output of the filter is sent to a quadratic rate detector where the results are expressed in decibels above a certain level defined in C^2/s. Detection in quadratic rate eliminates, up to a certain limit, the falsification of readings when the time between successive discharges is randomized. In that case, the reading is proportional to the energy dissipated in internal discharges.

6 Visualization of measurements

6.1 General

In view of the fact that it is the condition of the insulation system that is being assessed, the PD data recorded with one of the measuring devices described in Clause 5 should be processed appropriately. Since the degree of damage to the insulation system, and therefore the risk of failure, is directly related to the particular nature of the partial discharge source, it is necessary to obtain reliable information on the kind of partial discharge sources that are measured. Various types of visual data processing can be employed for this purpose.

6.2 Minimum scope of PD data presentation

To evaluate the PD behaviour, it is recommended that at least the classic parameters of partial discharge measurement, are used as follows:

- the PD magnitude, and
- the r.m.s. value of test voltage.

The PD magnitude, as the largest repeatedly occurring magnitude, can be expressed in terms of voltage [mV] or in terms of apparent charge [pC] and evaluated in accordance with IEC 60270. In principle, the measuring unit used for quantifying the PD magnitude is arbitrary. In the display obtained from these two parameters, the PD magnitude Q_m related to the test voltage U applied to the winding or winding element is shown as function $Q_m = f(U)$ for increasing and decreasing voltage. Here, the test voltage, in accordance with 9.1.5, is increased to a specified maximum value, either continuously or in suitably chosen steps, before being reduced to the minimum test voltage.

In addition, the inception voltage U_i (PDIV) and the extinction voltage U_e (PDEV) of the partial discharges from the test object, in accordance with IEC 60270, can be determined from the curve $Q_m = f(U)$ in Figure 3. The inception and extinction voltages are related to a specified low threshold value of PD magnitude. Consequently, the detection limit to assess PDIV and PDEV may significantly vary, depending on the background noise level during testing.

Figure 3 shows an example of the $Q_m = f(U)$ diagram. It is preferable to assign the voltage to the abscissa and the PD magnitude to the ordinate. The voltage axis is then linear scaled. Normalizing the voltage values to predetermined reference values, for example the maximum test voltage U_{max}, facilitates comparisons. The PD magnitude axis can be scaled either linearly or logarithmically.

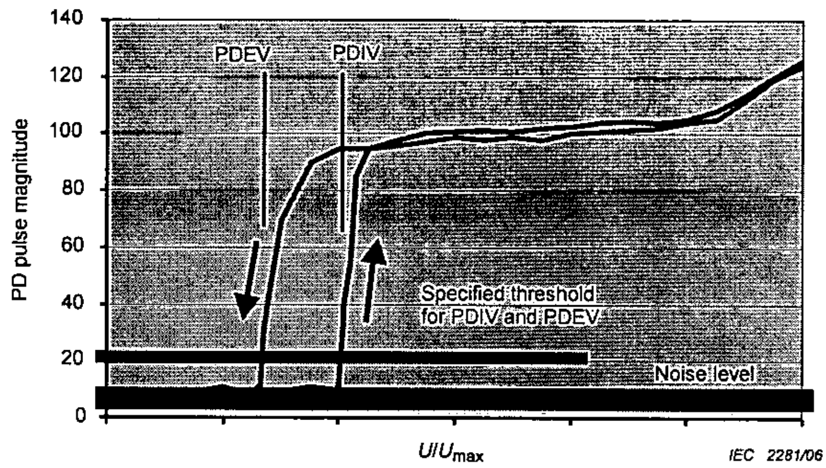


Figure 3 – PD magnitude as a function of the normalized test voltage $Q_m=f(U/U_{max})$

6.3 Additional means of PD data representation

6.3.1 General

When using digital PD measuring devices, the PD magnitude q_i is acquired for the train of PD pulses for each individual PD event that occurs during the measuring time and the associated instantaneous voltage u_i at time t_i or, for periodic a.c. voltages, the phase angle ϕ_i within the corresponding period of the power-frequency test voltage. In each case, the measured values of PD are recorded with a suitable type of measuring device and stored so that they can be analysed later by appropriate methods.

Additional quantities can be derived from the PD data like integrated charge, discharge current, quadratic rate, PD power, and PD energy in accordance with IEC 60270. The NQN quantity (normalized quantity number) can be used too. However, with digital systems, the derived PD quantities will depend on the specific instrument settings during testing, for example trigger level, etc. By using suitable diagrams during the subsequent analysis, it is possible to visualize the PD measurements so that the condition of the insulation system can be assessed. Either statistical distributions of PD parameters, phase-resolved or time resolved presentation of individual measured PD parameters, or so-called scatter diagrams of specific parameters can be employed for this purpose (e.g. pulse height distribution, pulse phase distribution, phase resolved pulse height distribution, oscillograms of pulse trains, PD distribution maps, etc.).

More detailed information on suitable PD pattern types and PD diagrams for further analysis can be found in reference [2][1], CIGRE technical brochure 226.

6.3.2 Partial discharge pattern

A partial discharge pattern can be viewed as a PD distribution map, in which specific PD quantities are correlated in a scatter plot, to obtain information on the sources of PD activity. Usually, a 2-dimensional PD distribution map is employed for visualization.

A PD pattern, which is recommended for identifying the causes of PD in stator winding insulation systems, is the ϕ-q-n pattern in which the PD magnitude q_i is on the ordinate and the phase of occurrence ϕ_i is on the abscissa for each individual PD pulse. In the scatter plot, the frequency of PD occurrence (n) within each phase/magnitude window should be visualized by employing a suitable colour code whose scale may be visualized by the side of the plot. Figure 4 shows an example of a ϕ-q-n pattern.

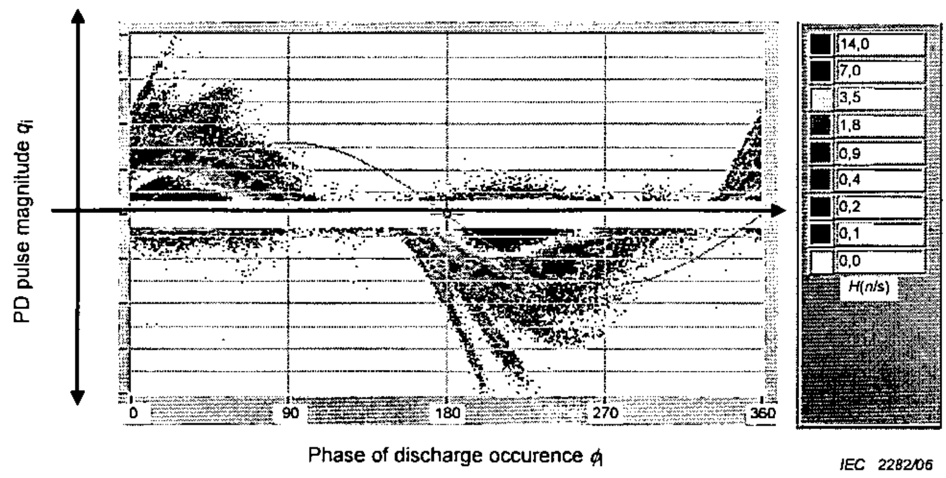


Figure 4 – Example of a ϕ-q-n partial discharge pattern where the PD was measured in series with the test object in accordance with Figure 5b, with colour code for the pulse number $H(n)$

[1] Figures in square brackets refer to the Bibliography.

7 Test circuits

7.1 General

The essential task of a test circuit for partial discharge measurements is to provide appropriate conditions for the detection of partial discharges within the test object. This is best achieved when the various components of the test circuit, not including the test object, are sufficiently PD free.

The test circuit comprises primarily:

- a high-voltage power supply conforming to IEC 60060-1 and IEC 60060-2;
- a voltage measuring device;
- a suitable PD coupling unit;
- a connection cable from the measuring impedance to the PD device with sufficiently low damping characteristics and good shielding;
- a partial-discharge measuring system;
- high-voltage connections.

To ensure that the test circuit does not influence the measurement of partial discharges from the test object, the arrangement should first be tested up to the maximum test voltage in accordance with the test procedure given in 9.1.6. The noise level produced by the complete test circuit at maximum required test voltage shall not exceed 100 pC when using the normalization procedure in accordance with Clause 8.

In case the test arrangement is not sufficiently free of interference to allow the measurement of the specified low threshold value of PD magnitude, an impedance or filter can be introduced at the high voltage between the test object and the high voltage source. This serves to attenuate disturbances from the high voltage source, for example PD from the testing transformer, the high voltage conductors or from bushings, or higher harmonics of the test voltage within or close to the bandwidth of the measuring system. Further information on external noise, disturbances and measuring sensitivity can be found in Annexes C and D.

The whole test circuit should be of a low-inductance arrangement. It is essential that ground loops are avoided. Low inductance leads are recommended as ground connections.

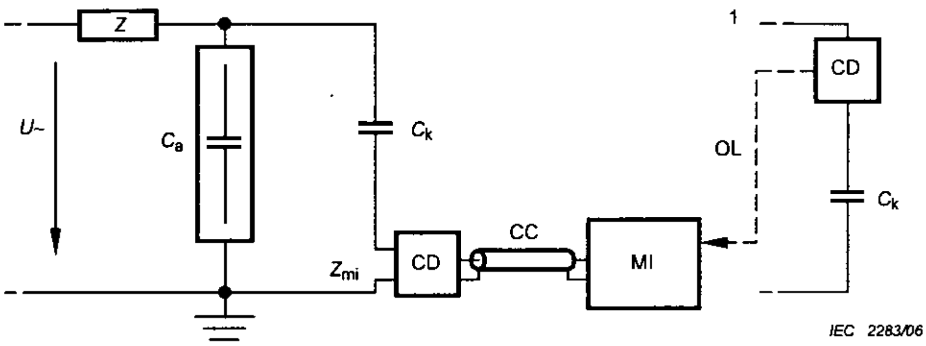
7.2 Individual winding components

For partial discharge measurements on individual winding components (stator bars, coils, etc.) it is preferable to use two basic test circuits conforming to IEC 60270. These circuits are shown in Figure 5.

The low voltage coupling device in the circuit of Figure 5a is placed on the ground side of the coupling capacitor. This arrangement has the advantage of being suitable for test objects with one grounded terminal, the test object being connected directly between the high-voltage source and ground. In the event of insulation failure during testing, the measuring equipment is not subjected to dangerous high voltages.

In the circuit of Figure 5b, the low voltage coupling device is placed on the ground side of the test object. The low-voltage side of the test object should therefore be isolated from ground. This test circuit might produce better sensitivity for low capacitance components compared with Figure 5a. The polarity of measured PD signals will be reversed for Figures 5a and 5b.

In both test arrangements, a protection circuit designed to withstand the breakdown current of test objects, which might fail during testing, should be combined with the coupling device.



1 = Alternative position for CD

Figure 5a – Coupling device (CD) in series with the coupling capacitor

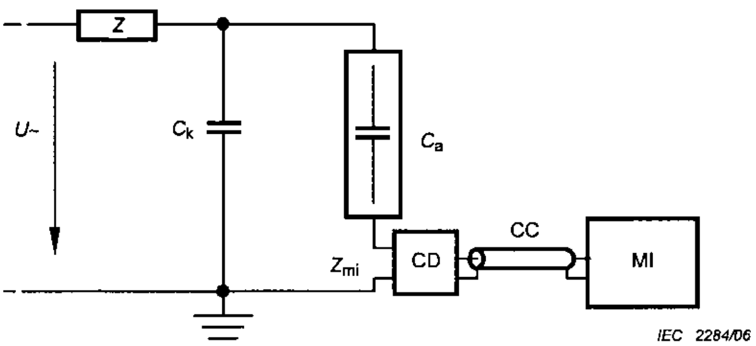


Figure 5b – Coupling device (CD) in series with the test object

Components

$U_{\sim}$ high-voltage supply
Z_{mi} input impedance of measuring system
CC connecting cable
OL optical link
C_a test object
C_k coupling capacitor
CD coupling device
MI measuring instrument
Z filter

Figure 5 – Basic test circuits in accordance with IEC 60270

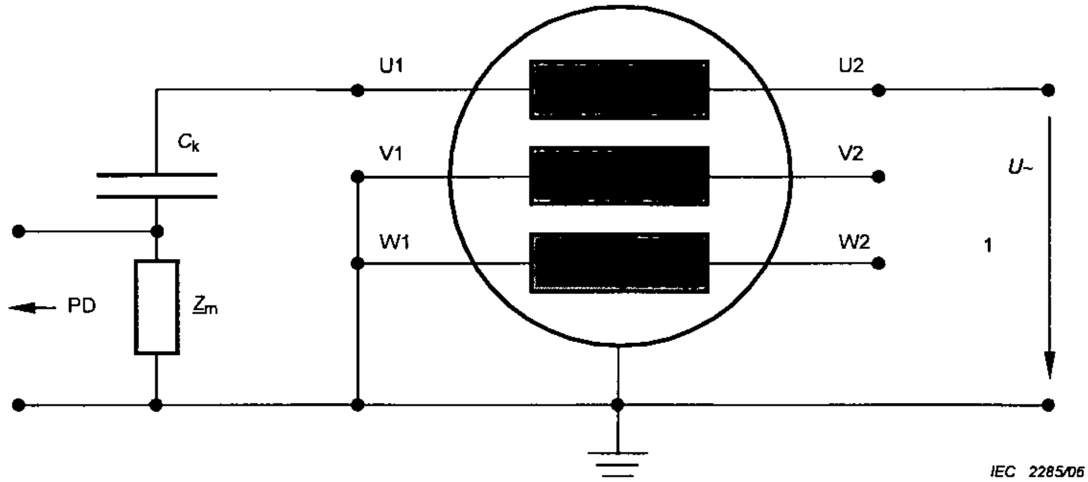
7.3 Complete winding

7.3.1 General

The information that can actually be obtained from partial discharge measurements taken on high-voltage windings depends on the accessibility of the star point and on the method of connection chosen for the measuring device.

The high voltage source and the PD coupling unit should be connected to opposite winding terminals whenever possible, to utilize the advantage of the damping effect of the winding phases to suppress conducted interference from the power supply. The PD coupling unit should be installed as close to the winding terminals as possible. The stator core should normally be grounded.

In Figure 6, a test circuit is shown for a PD measurement on phase U with terminals U1, V1, W1 being the high voltage phase terminals and U2, V2, W2 being the star point side of the winding.



1= high voltage supply

Components

$U_\sim$ high-voltage supply

$\underline{Z}_m$ measuring impedance

C_k coupling capacitor

Figure 6 – Test circuit for PD measurement (S1.1) on complete winding

7.3.2 Recommended standard measurements (SX.X)

For measurements on windings with open star point, the winding connections given in Table 1 are recommended. Table 2 shows the measurements recommended for closed accessible and inaccessible star points. To check the production quality after manufacturing and to have a baseline measurement, which facilitates future comparison and trending of partial discharge results, it is recommended to perform the measurements listed in Tables 1 and 2 on new and used windings.

Table 1 – Connection diagram S1 for open star point

ID number	HV	Ground	C_K
S1.1	U2	V1W1	U1
S1.2	V2	U1W1	V1
S1.3	W2	U1V1	W1
S1.4	U2V2W2	-	U1V1W1

Table 2 – Connection diagram S2 for closed star point

ID number	HV	Ground	C_K
Accessible star point			
S2.1	U2V2W2	-	U1V1W1
Inaccessible star point			
S2.2	U1V1W1	-	U1V1W1

A comparison of measurement results from S1.1 to S1.3 with measurement S1.4 for open star point (Table 1) allows for the detection and distinction of specific partial discharge sources between two phases of the winding, for example due to manufacturing deficiencies or as a result of ageing during operation (see 9.2).

Depending on the characteristics of the available power supply and the capacitance of the winding, it may not be convenient or even feasible to energize the whole winding. Then the measurement S1.4 on the complete winding to ground for open star point in Table 1 can be left out. In case of new windings, it may be decided, for example for smaller machines, to apply a simplified test procedure after manufacturing even for open star point by performing only measurement S1.4. This, however, provides less information for future comparisons and trending of the winding condition and gives no indication of possible discharges between two phases of the winding.

In cases where conducted interference from the power supply can be excluded, both ends of the winding terminals, i e. the phase and neutral side (U1U2, V1V2, W1W2) for measurements S1.1 to S1.4 and S2.1, can be connected, to obtain equal sensitivity for insulation defects and/or manufacturing deficiencies at both sides of the winding.

7.3.3 Optional, extended measurements (EX.X)

In addition to the standard measurements given in Tables 1 and 2, further extended measurements can be made optional, to investigate the PD behaviour of the winding insulation in more detail. These measurements are listed in Tables 3 and 4. Measurements should be selected appropriately, if the results of standard measurements indicate specific discharge sources that need further investigation. Whether or not, and what specific kind of extended measurement is needed, shall be decided by the operator or manufacturer.

Table 3 – Connection diagram E1 for open star point

ID number	HV	Ground	C_K
E1.1	U1	V2W2	U2
E1.2	V1	U2W2	V2
E1.3	W1	U2V2	W2
E1.4	U1V1W1	-	U2V2W2

Table 4 – Connection diagram E2 for closed star point

ID number	HV	Ground	C_K
Accessible star point			
E2.1	U2V2W2	-	U1
E2.2	U2V2W2	-	V1
E2.3	U2V2W2	-	W1
E2.4	U1V1W1	-	U2V2W2
Inaccessible star point			
E2.5	V1	-	U1
E2.6	W1	-	V1
E2.7	U1	-	W1

By using the extended measurements listed in Tables 3 and 4 as a supplement to the standard measurements of Tables 1 and 2, more detailed information can be obtained about the specific location of dominating discharge sources within the stator winding system, since these tests utilize the attenuation of pulses when travelling along the winding.

8 Normalization of measurements

8.1 General

Due to pulse propagation, resonance and mutual cross coupling in machine windings, mentioned in 4.3, calibration is not possible. The aim of normalization is to ratio out various influences of the test circuit, for example power supply connections, stray capacitance, coupling capacitance and test object capacitance, by injecting a well-defined reference pulse at the machine terminals with the complete test circuit connected. Normalization is to ensure that the PD measuring system provides sufficient sensitivity to measure a specified value of PD magnitude correctly, as it appears at the machine terminals during the measurement, and to show that the PD detection system used, is responding in a repeatable fashion. In addition, normalization of the test circuit facilitates comparisons between measurements on objects having the same design, taken with the same PD device. Normalization of the test circuit should be performed by injecting short-duration current pulses of known magnitude by means of a reference pulse generator (calibrator) conforming to the specifications given in IEC 60270.

The following points are important to emphasize:

- normalization does not define the unknown, machine-dependent signal transfer function between the actual PD source in the winding insulation and the location of the installed sensors, which is in general a function of the location of the PD source and the individual winding design;
- normalization at the machine terminals does not adequately represent the PD pulses that actually occur at an unknown location within the stator winding. Consequently, the process of normalizing a measurement on complete windings does not provide a measure for quality of the insulation system in terms of absolute quantities;
- normalization cannot provide a benchmark for direct comparison of different machines.

Since pulse propagation phenomena need not be considered when testing fully processed coils, bars and other individual winding components which can be treated as lumped capacitance, normalization in terms of PD magnitude in accordance with IEC 60270 can also serve as a basis for absolute comparison of different objects and can thus give a measure of quality, for example for quality assurance testing during manufacturing.

8.2 Individual winding components

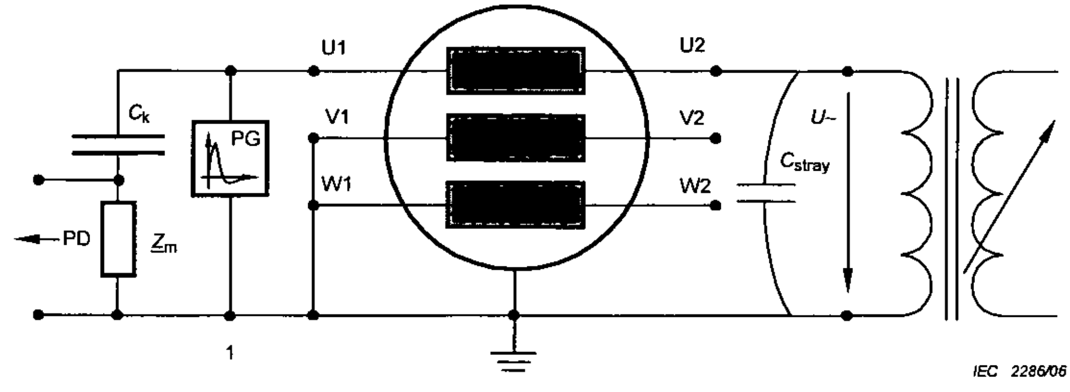
For testing individual winding components, the test circuit described in 7.2 should be normalized in accordance with the calibration procedure given in Clause 5 and Figure 4 of IEC 60270, by injecting current pulses of a specified pulse magnitude, with the complete test circuit designed for the subsequent measurement. This is performed by means of a reference pulse generator connected between the terminals of the test object and the high voltage supply connected to the test arrangement but not energized.

The normalization should be performed at one magnitude in the relevant range of magnitudes expected, to assure good accuracy for the specified PD magnitude. For individual winding components, the measurement of PD magnitude, in terms of apparent charge q in [pC] and in accordance with IEC 60270, is recommended.

8.3 Complete windings

For testing complete windings, the normalization of the test circuits described in 7.3 is performed by injecting current pulses of a specified PD magnitude at the machine terminals or at the location of the PD coupling unit, by means of a reference pulse generator. This is to simulate PD pulses as they appear at the machine terminals during the measurement. However, it should be noted that the use of pC or mV cannot provide a benchmark for direct comparison of different machines, or if different PD detectors are employed.

Normalization is in principle needed for each type of test circuit arrangement described in 7.3, before starting the actual PD test. In case a sequence of PD tests is performed, for example S1.1, S1.2, S1.3, in which the symmetry of the three-phase winding can be utilized, normalization is necessary only for the first of those measurements.



1 PG = Pulse generator according to IEC 60270

Components

$U_{\sim}$ high-voltage supply

$\underline{Z}_m$ measuring impedance

C_k coupling capacitor

C_{stray} stray capacitance

Figure 7 – Normalization of the test circuit for measurement S1.1

Depending on the size of the individual machine under test, a separate normalization of each phase may be advisable, since for very large machines symmetry of the three phases may not necessarily apply because of the influence of circuit ring connection design.

The procedure of normalization for complete windings in accordance with Figure 7 should be performed as follows:

a) the test circuit is selected in accordance with 7.3, depending on the type of measurement to be performed (see Tables 1 to 4);
b) all connecting leads to the phase terminals, the PD coupler and the test voltage supply should be as short as possible and all components of the test circuit should be in the final arrangement for measurement with the test voltage supply connected but not energized;
c) the reference pulse generator is connected between the phase to be tested, and ground, with leads as short as possible to avoid distortion of the signal because of lead inductance. If possible the reference pulse generator should always be connected directly to the phase terminal;
d) the pulse generator should be adjusted to an adequate pulse magnitude in the relevant range of magnitudes expected from the test object;
e) the reference pulses of constant magnitude are measured by the PD device to determine a scale factor for subsequent measurement.

Since the entire arrangement of the test object, connecting cables and measurement device with filter and amplifier needs to be considered from a system perspective, the normalization of an individual test circuit for complete stator windings will still only hold for a given machine and a given detection system. It is important to emphasize that a normalization is always needed if the new testing arrangement differs from that of the previous measurement so that no winding symmetry can be utilized.

In principle, more sophisticated normalization procedures could be performed, which provide information on pulse damping and cross-coupling effects of travelling pulses within the winding. However, these procedures are beyond the scope of this specification.

9 Test procedures

9.1 Acquiring PD measurements on windings and winding components

9.1.1 General

Off-line PD measurements may be obtained on complete windings, individual phases, or individual winding components. In the case of complete or partial windings, the test object shall be disconnected from all external power supplies, bus work, surge arrestors, surge capacitors, and excitation systems. Where possible, the point of test lead contact should always be at the machine terminals. Under no circumstances should the contacts be made at the circuit-breaker. In all subsequent tests, the entire test circuit, including all components in accordance with Clause 7, should be arranged in the same way as for the initial measurement to ensure that measurements can be compared. Furthermore, it is important that the measurement system used in accordance with Clause 5 and the normalization procedure applied in accordance with Clause 8 are always the same to obtain comparable measurement results, for example for trending. In addition, the actual test conditions should be well-documented in the test report in accordance with Clause 11.

9.1.2 Test equipment and safety requirements

The test voltage supply used to energize the winding should be sufficiently PD free, in accordance with Clause 7, over the range of applicable test voltages. The waveform of the applied voltage should have $U_{pp}/U_{rms} = 2\sqrt{2}$, ± 5%. The voltage supply should also have sufficient apparent power (kVA) rating to energize the winding. If such a unit is not readily available, some form of reactive compensation can be used in parallel or in series with the test source. As an alternative, it is acceptable to perform PD tests at lower frequencies, for example by using equipment that supplies power at 0,1 Hz, or at higher frequencies up to 400 Hz when using a resonance test system. In this case, it should be noted that the PD results obtained from very-low frequency tests might significantly differ from that at power frequency and thus direct comparison might not be possible [3]. Whichever method is chosen, any subsequent tests should be performed using the same power supply to allow trending of the test results over time.

Applicable safety requirements of the high-voltage PD test include, but are not limited to, the following:

a) the circuit shall be equipped with reliable over-current relay or contactor to disconnect the power supply in the event of failure or flashover;

b) all high-voltage connections to the stator winding terminals should be as short as can be reasonably achieved, and shall have secure attachments to avoid inadvertent disconnection during the test. A grounding stick should be available;

c) the area immediately surrounding the test object should be clearly marked off using highly visible barriers;

d) at least two persons should be in attendance during the process of making connections and applying voltage.

NOTE Health and safety rules and regulations may be applicable during the test.

9.1.3 Preparation of test objects

Before starting the test, the stator should be inspected for cleanliness. Furthermore, sufficient air clearance between adjacent phase connections and between internal cables within the winding are needed. Cables should not touch each other, or any surface at different potential.

To ensure that the winding insulation has sufficient dielectric strength for the test, it is recommended to check the insulation resistance before starting the PD test, which should generally be above 100 MΩ when corrected to 40 °C [4]. Measurement of the insulation resistance will reveal whether or not the winding is excessively dirty, damp or if the insulation is damaged. If the insulation resistance is insufficient, it is advisable to take electrical measurements after the winding has been cleaned and dried and/or the source of the low insulation resistance value has been located. However, subject to agreement between tester and purchaser, the machine may be PD tested without further treatment.

Individual winding components (e.g. coils, bars, or winding sections such as statorettes) should be carefully prepared before any high voltage is applied. They should be clean and dry with the final corona protection applied. Electrical field enhancements at the ends of the components should be avoided, with all strands being in good contact. The conductive slot coating should be in contact with ground potential throughout its whole length to form an equipotential surface. A thin, flexible copper wire, stranded wires, metallic foils or suitable slot models are recommended.

9.1.4 Conditioning

PD will typically decrease during the first minutes of voltage application and thus conditioning will ensure more stable PD behaviour of the winding or winding component to be measured. Therefore, the test object should be conditioned immediately before the test by energizing for several minutes before acquiring PD data. To avoid over-stressing the winding, the applied voltage should be carefully chosen based on the winding condition. For new and used windings, a conditioning period for about 5 min at the maximum test voltage (see 9.1.5) is recommended. Conditioning may be useful also for individual winding components. Following the conditioning cycle, the voltage may then be re-applied to start the partial discharge measurements.

9.1.5 Test voltages

For the PD test, the test object is connected to the circuit in accordance with Clause 7 and the increase in applied voltage is made either in suitably chosen steps (e.g. $\Delta U = 0{,}2\ U_{max}$) or by a continuous ramping ($\leq$ 1 kV/s) up to the maximum test voltage U_{max}.

In the case of a stepped voltage increase (see Figure 8a), a dwell time on each step of at least 10 s is recommended to record the relevant PD parameters including the PD pattern at each voltage step.

In case of a continuously ramped test voltage, the power supply needs to be sufficiently PD free during voltage regulation.

The maximum applied test voltage U_{max} for new windings and winding components should be selected from the following voltage levels:

$U_1 = U_N / \sqrt{3}$, or operating (line-to-ground) voltage of the insulation system;

$U_2 = 1{,}2\ U_N / \sqrt{3}$, or 120 % of operating (line-to-ground) voltage of the insulation system;

$U_3 = U_N$, or rated line to line voltage of the insulation system.

Higher test voltages may provide additional information.

NOTE For used windings, the ramping rate and maximum test voltage should be agreed between tester and purchaser.

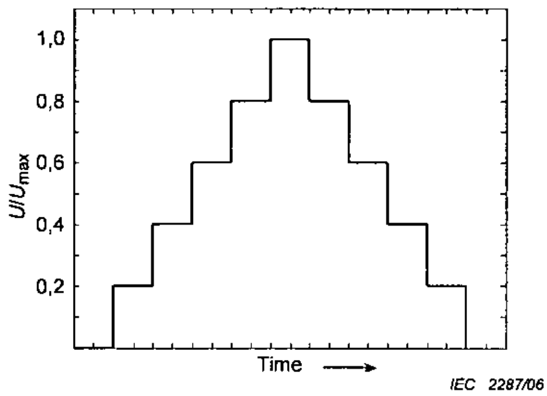


Figure 8a – Gradual stepped power-up in steps of U/U_{max} = 0,2

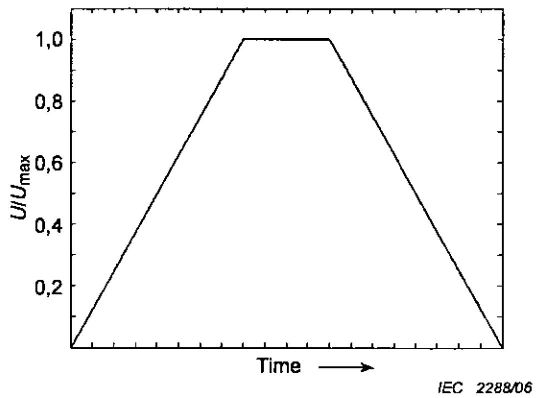


Figure 8b – Continuous power-up with ramped test voltage

Figure 8 – Test voltage applied to the test object during PD measurement

9.1.6 PD test procedure

9.1.6.1 Background noise assessment

Before starting the PD test, the level of background noise associated with the measurement arrangement should be obtained to ensure that the test arrangement has sufficiently low noise and PD up to the maximum test voltage. This should be performed with the PD measuring arrangement fully prepared for the test, preferably by replacing the test object by an appropriate discharge free capacitor, or if such a capacitor is not available by running the entire test arrangement at no-load with power supply, PD coupling unit and PD measurement device and only the test object being disconnected, up to the maximum test voltage. In the case of the no-load test, the test circuit needs to be normalized separately for the no-load condition to gain reliable PD values. If ramped voltages are to be applied during subsequent testing, the no-load test should be done with the same slope.

9.1.6.2 Reducing the influence of noise and disturbance

Noise resulting from sources inherent in the measuring equipment cannot practically be eliminated, for example thermal noise in accordance with Annex C (noise, disturbance and sensitivity). Disturbances, which are assumed to result from external components, can be reduced or even eliminated by appropriate measures. In a first step, it is necessary to localize such disturbance signals when they appear and to take appropriate measures to minimize them. In general, the following guidelines can be given to optimize the measurement arrangement:

- use a proven combination of PD coupling unit and measuring equipment;
- place the coupling unit as close to the test object as possible, to reduce damping between the test object and the coupler;
- connect the power supply and the PD coupling unit to opposite winding terminals in accordance with Clause 7 to ensure that disturbances from the power supply will be attenuated when propagating through the winding;
- when testing complete stator windings ensure that the leads of all embedded temperature detectors (RTDs) are anchored to the grounded stator frame;
- the arrangement of transformer and PD coupling unit needs to be normalized and tested separately to get meaningful information about the magnitudes of the disturbances;
- normalization and measurement of the test arrangement is recommended before every usage. Depending on the location and time of measurement, the quality of the supply net may change and/or the transformer may get more and more dirty over longer times. Furthermore, the transformer insulation may age, or whatever may happen;
- in general the grounding of the test object and the measuring device has to be good (large area grounding). If possible, the same connection point for the PD coupler, the test object and the measuring equipment should be used;
- build the test arrangement as compact as possible. Short measuring cables, short ground leads and compact circuit dimensions reduce the inductance and also any electromagnetic coupling into the test circuit by antenna effects;
- some measuring cables need a matching resistor to avoid reflection. Only proven cables should be used for the same reason;
- some electronic device, for example computers and monitors, may cause interference to the measuring device. Often positioning these devices into another direction can reduce such influences on the measurement.

9.1.6.3 PD testing

With the PD measuring circuit fully prepared for the test in accordance with Clause 7, the test voltage is applied to the test object as described in 9.1.5. At each voltage step, or during continuous ramping, the PD data recommended in Clause 6 should be recorded and processed to provide appropriate PD data presentations. To provide the $Q_m = f(U)$ curve as well as PD inception (PDIV) and extinction voltages (PDEV) in accordance with Clause 6, the measurement should be performed with increasing and subsequently decreasing test voltage as shown in Figure 8. The same rate of change during voltage increase and decrease should be applied.

If the partial discharge values during voltage application are recorded electronically and stored in files of measured values, the diagrams recommended in Clause 6 can be obtained and further evaluation as described in Clause 10 can be carried out to assess the measured PD results. This may include the distribution of pulse magnitudes, phase resolved distributions or specific PD patterns (see Clauses 6 and 10) at various levels during test voltage increase and decrease.

Any comments or observations during the test should be recorded to benefit future reference. Depending on the machine being tested and the aim of the test, an appropriate sequence of standard measurements and/or optional extended measurements as described in Clause 7 should be taken.

9.2 Identifying and locating the source of partial discharges

9.2.1 General

The electrical measurement of PD at the terminals of the specimen evaluates the intensity, frequency, and polarity of discharges, when using instruments that provide the PD parameters in accordance with 6.3. However, to translate these parameters into useful information about the winding condition, it is important to identify the location of the source of the partial discharges.

Initially, the PD test is generally performed on individual phases while the other two phases are held at ground potential. This will provide a characteristic PD distribution or PD pattern for each phase. Following the per-phase test, and assuming that a power supply of sufficient apparent power (kVA) rating is available, the first and most basic method of determining discharge origin under off-line test conditions is to use the test voltage source to energize simultaneously all three phases of the winding. Under these conditions, the effect of phase-to-phase voltage gradient in the end-winding is removed. If all three phases are energized at once, discharges associated with phase-to-phase activity in the end-winding will be eliminated from the PD signature. Phase-to-ground discharges may still be evident, the causes of which should be thoroughly investigated. A corresponding decrease in PD magnitude and pulse count suggests that the end-winding is contributing to the signal obtained during the per-phase measurement. This is a useful means of segregating end-winding PD from discharges in the slot.

To locate the source of a specific problem, it may be helpful for the diagnostic process to subdivide the winding, if possible. However, since machine manufacturers will run together pole jumpers, circuit rings, and cables from one phase so that these elements are in contact with one another, in this situation, with one circuit grounded while the other is energized, an abnormal condition exists and high PD discharge levels may be recorded.

NOTE In cases where it is necessary to test a subdivided winding, the purchaser and tester may consult the machine manufacturer for guidance before starting the operation.

A variety of supplementary test methods has been developed, making use of the different physical effects of partial discharges. To confirm the presence or absence of end-winding discharge, it is a useful practice during these tests to examine the winding from both ends using a viewing scope or camera capable of detecting corona discharge. It is an advantage of off-line tests that such inspections can be performed with covers and rotor removed, if required.

The following description deals with the very popular electrical method of localization. Non-electrical methods of locating PD sources are described in Annex B.

9.2.2 Electromagnetic probes

The use of electromagnetic probes to locate sources of PD requires scanning of stator slots (after removal of the rotor), slot exit areas or end-winding area at different applied voltages. In addition to obtaining measurements at U_1, it may be desirable also to take similar measurements at discrete intermediate voltage steps < U_1. Typically, these types of probes are best utilized when data can be compared to an established database that enables ranking of the machine being tested.

It should be noted that PD activity might not be restricted to the machine end-winding. Conduit boxes, cable routing, termination boards and stand-off insulators, etc. can initiate PD, and should be included when using the probe test method. It should be noted that probes can disrupt the electric field, possibly inducing spurious discharges. For PD detection within the end-winding with such probes, additional safety requirements for the test personnel need to be considered.

10 Interpretation of test results

10.1 General

In general, factory PD testing of windings and winding components is intended to ensure consistent manufacturing quality, whereas on-site PD testing of windings is to determine the degree of ageing due to the various ageing factors during operation. Thus, interpretation of results obtained from these tests is the final, most important step after the PD measurements have been taken. Depending on the test results, it has to be decided whether there are any indications of defects and, if so, what they imply regarding the performance of the insulation system, whether any supplementary tests are needed and the planning and/or implementation of any essential corrective maintenance.

It should be noted that individual machines are usually subjected to specific stress profiles during operation and that there is a great variety of design features, production conditions and various insulation systems from different manufacturers. This usually leads to significant variations in the amounts of partial discharges depending on the individual properties of the machine being tested. As a result, a direct comparison of different types of machine in terms of absolute values is not possible.

Neither is it possible to establish any absolute limits for complete windings, for example as acceptance criteria for use during production or operation. Therefore, no specific limits that can be used for quality assessment will be given in this specification.

To improve the interpretation of PD test data obtained on complete stator windings, the results from previous inspection reports, for example from visual inspections, should be carefully examined and considered for condition assessment.

10.2 Interpretation of PDIV, PDEV and Q_m

10.2.1 Basic interpretation

The basic results to interpret from any off-line PD test on windings and winding components are the PD inception voltage (PDIV), the PD extinction voltage (PDEV) and the largest repeatedly occurring PD magnitude referred to as Q_m, measured at increasing and decreasing test voltage, in accordance with 6.2.

Even if the PD site, which produces the highest PD magnitude is not necessarily the location in the winding being at most risk, detection and interpretation of PD magnitude as a function of test voltage provides a simple and effective means of characterizing typical dominating PD sources.

Interpretation is always comparative for complete stator windings. That is, it is not generally possible to specify an acceptable level of Q_m, or a level of Q_m where there is a high risk of insulation failure. As described in Clause 8, this is related to the inductive, capacitive and transmission-line nature of a stator winding, as well as the fact that PD is often only a symptom of the failure process, not a direct cause. However, meaningful interpretation for complete windings can occur by

- trending Q_m on the same stator over time, using the same test method and equipment with the same technical characteristics;
- comparing Q_m from several stators with the same design, using the same test method and equipment with the same technical characteristics;
- comparing Q_m between different phases of one stator, using the same test method and equipment with the same technical characteristics.

PD results on individual coils or bars are measured in pC, and the PD magnitudes are absolute. This allows comparison of the PD magnitudes between different coils or bars, and indeed measurements from different test apparatus. On individual winding components, the discharge inception voltage (PDIV) and discharge extinction voltage (PDEV) are measured with a maximum specified noise background in pC.

In general, the higher the PDIV and PDEV the better impregnated the winding or winding components are for the same design and the less insulation deficiencies are present.

10.2.2 Trend in PD in a machine over time

This is the most powerful means of interpreting PD magnitude data on complete stator windings, no matter which detection method is used. One should first obtain an initial fingerprint of the off-line PD activity. The initial fingerprint is best when the winding is new. If the winding deteriorates due to operation in service, then Q_m will usually increase over time. For example, doubling of Q_m over one year may be an indication that significant deterioration has occurred. Additional off-line tests, PD probe tests or a visual inspection of the winding may then be warranted.

Some cautions with regard to PD trending over time are:

- a new stator may have relatively high PD that decreases after the first 5 000 to 10 000 equivalent operating hours;
- for the trend to be meaningful, the trend plots should only show data collected at the same voltage, temperature and similar humidity conditions, using the same PD detector. As far as possible, between tests, the test voltage should be within ±2,5 %, the temperature of test object should be within ±10 °C. For hydrogen cooled machines, it is recommended to perform the measurement under atmospheric air conditions, but in any case under the same gas and pressure conditions as the previous test;
- variations of Q_m of a certain percentage, for example ±25 %, are normal, due to unavoidable changes in test conditions and more or less statistical behaviour of PD processes.

If the trend over time is high, or the individual reading is high in comparison with similar stator windings or coils, then the PD data can sometimes be further analysed to determine the probable cause for the high PD activity. In this case, the analysis of phase resolved PD patterns (Figure 4) in accordance with 10.3 is useful for identifying the PD sources.

10.2.3 Comparisons between winding components or between windings

Another effective way to determine if one winding or winding component is different from another is to compare the PD quantities between winding components or between windings. Different comparisons are possible.

a) *Factory tests on winding components*

   Direct comparisons can be made in the PDIV, PDEV and Q_m when the measurements are made in accordance with the procedures in IEC 60270, irrespective of the component design or measuring equipment. The results of such tests can be used to determine if there has been a change in processing or insulating materials used in the component. Usually, only a small percentage of winding components are subjected to PD tests.

b) *Factory tests on windings*

   When comparing PD results between similar machines, the most reliable comparison occurs when all the stators are identical including having the same insulation system, and the tests are done at the same voltage, with similar temperature and humidity conditions in accordance with 10.2.2. The tests shall also be performed with the same PD test equipment operating at the same frequency range using the same test arrangement. As for trending over time (10.2.2), variations in Q_m of a certain percentage, for example ±25 % between machines is not significant. The purpose of such comparison tests in the factory is to establish the relative quality of the materials and processing used to manufacture the winding. Purchasers of windings can seek from manufacturers assurance that a new winding was made with the normal quality level that the manufacturer has achieved in the past. That is, for example, Q_m for the winding at the specified test voltage is lower than 95 % of the mean Q_m magnitudes achieved by the manufacturer on the same windings they have made in the past.

In some cases, the manufacturer may compare the PD quantities from a new winding to similar windings they have made in the past. In this context, the manufacturer may have experience that indicates that a group of different designs have the same statistical distribution as the PD quantities. Generally, similar machines will be of the same design, be the same type of machine (motor, turbogenerator, etc.) and have the same voltage rating.

Due to differences in processing and materials, as well as likely differences in PD test methods, comparisons in PD quantities on complete windings should not be made between different winding insulation system designs or different manufacturers.

c) *On-site test on windings*

Comparisons can be made between windings of the same design, manufacture and ratings, to estimate which winding may have been subjected to the most in-service ageing. Windings with higher Q_m at the same test voltage, or lower PDIV and PDEV, in general will be more deteriorated. The windings shall be tested with the same test equipment using the same frequency range.

10.3 PD pattern recognition

10.3.1 General

If the PD data in accordance with 6.3 are recorded for each PD event during the measuring time, an alternative way to interpret the PD activity during off-line measurements can be utilized. For this, ϕ-q-n–patterns in accordance with Figure 4 are used. Since the degree of deterioration, and hence the risk of insulation failure, depends considerably on the specific type of partial discharges, it is crucial to have sound information on the source of any PD activity, i.e. on the type and possible location within the stator winding or winding element.

When using the ϕ-q-n patterns, it may be possible to separate various PD sources from each other, to assess the related risk and to trend them separately. When knowing the physical process behind – or the location of theses separated sources – it is also possible to weight their risk separately. This should be done, because there is little correlation between the PD magnitudes and the ageing process these PD patterns indicate.

For example, it may happen that two sub-patterns, appearing in one PD reading, may reach similar PD magnitudes: one caused, for example by delaminations within the main insulation of the slot section, the other caused, for example by surface effects somewhere in the end-winding. Although both phenomena generate PD that may reach similar magnitudes, the delamination PD in the slot section indicate a more critical insulation condition, caused by overheating and/or thermal cycling, than the surface PD in the end-winding area, for example caused by contamination or elevated humidity.

10.3.2 Basic interpretation

A basic procedure that can be applied for the identification and localization of typical PD sources in windings, by using phase resolved PD patterns, is shown in Figure 9. Each sub-pattern that can be separated from the complete PD reading can be classified in this way.

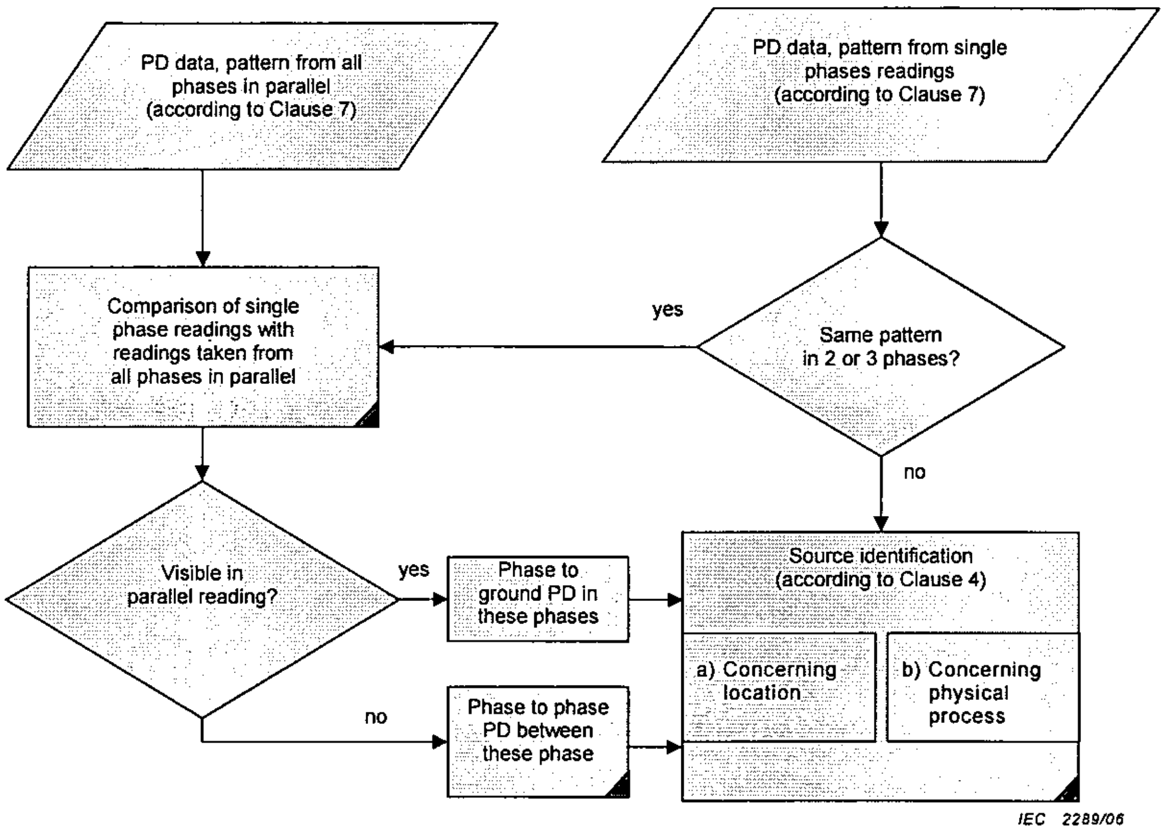


Figure 9 – Example for identification and localization of PD sources

The aim of PD pattern interpretation is to separate PD resulting from various PD sources within the test object. With this information, it is possible to (see Annex E)

- observe the trend behaviour of each PD source;
- localize the various PD phenomena;
- provide rough information concerning location for pinpointing;
- assess the insulation condition, depending on PD source and PD location.

When analysing phase resolved PD patterns, again the most meaningful interpretation can be obtained by

- trending the PD pattern on the same stator over time, using the same test method and equipment with the same technical characteristics;
- comparing PD patterns from several stators with the same design, using the same test method and equipment with the same technical characteristics;

– comparing PD patterns between different phases of one stator, using the same test method and equipment with the same technical characteristics.

To facilitate comparison between test results a suitable database of PD measurements should be utilized. This database should ideally include a complete history of the PD behaviour and the operational and maintenance data of each machine under test.

Furthermore, it is advisable for the database being used to incorporate PD test results that can be visualized in accordance with Clause 6 so that typical PD patterns can be compared directly with those obtained from new measurements. When using such a database, the PD test results, quantified in accordance with Clause 6, may be assigned to specific sources of PD.

The specific relationship between the source of the PD, its typical behaviour and also its implications for the risk of insulation failure, is usually based on past experience verified in practice. In addition, the database can also be utilized for the direct comparison of PD results with those of machines of similar design and insulation system, which provides further useful information.

11 Test report

The test report should contain all data necessary for future trend analysis, as well as a clear recommendation to the operator on the condition of the machine.

The test report should contain the following items.

- Machine data
  - manufacturer
  - type and serial number
  - year of manufacture
  - original winding/date of rewind
  - rated voltage
  - rated current
  - rated apparent power
  - rated power factor
  - rated frequency
  - insulation class/maximum permitted winding temperature
  - insulation system
  - stator cooling system/media
    - indirect air/hydrogen/carbon dioxide
    - direct cooled/air/hydrogen/water
- Owner's data
  - owner
  - location
  - unit

- Operational data [2)]
  - operation mode (continuous/intermittent)
  - inverter driven
  - total and/or equivalent operating hours to date
  - total starts to date, if available categorized in hot, warm and cold starts
  - number of trips to date
  - maximum winding temperature and conditions
  - average winding temperature
  - important events to date
- Test circuit and equipment
  - description of the test circuit
  - test equipment used
    - manufacturer
    - type
    - serial number
    - calibration date and certificate number
    - capacitance of the coupling capacitor (if used)
  - measuring bandwidth of the PD measuring system
- Test conditions
  - test specialist
  - date
  - ambient temperature
  - stator winding temperature
  - relative humidity
  - ambient air pressure
  - state of the machine/stator winding (normal cooling medium/pressure, or open at ambient condition)
- Test results
  - insulation resistance
  - instrument settings
  - test voltage levels /ramping rate
  - conditioning process
  - normalization/calibration factor per connection if relevant
  - noise level
  - sources of ambient disturbances if known
  - PDIV, PDEV, $Q_m=f(U)$
  - threshold value for PDIV and PDEV
  - pulse repetition rate for Q_m if available
  - phase-resolved discharge number distribution if available
  - phase-resolved discharge height distribution if available

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2) Recommended data to improve interpretation of PD test results

  - oscillogrammes of pulse trains if available
  - phase-resolved partial discharge patterns if available
- Diagnosis and recommendations
  - based on
    - measurement results
    - comparison with earlier measurements if available
    - observations made during the measurement
    - if available, a reference database may be used for determination of the nature of the discharges measured

NOTE It is advisable to store the measurement results in the most original data-format for future reference.

Annex A
(informative)

On-line partial discharge measurements

On-line PD tests refer to measurements performed while the generator or motor is operating normally. Such tests can be performed using coupling devices that are temporarily or permanently installed. A range of such techniques has been developed by a number of organizations, some of which are commercially available. Details of all of the industrially important methods are provided in IEEE 1434-2000 [1]. This document contains extensive discussion and descriptions of the origin, consequences and detection of PD using on- and off-line techniques.

The main advantage of on-line measurements is that they are recorded with the rotating machine experiencing all of the operating stresses; thermal, electrical, environmental and mechanical. Consequently, if the measurement is performed properly, this method affords the highest probability of assessing the ability of the machine to continue to operate reliably. On-line PD testing has the following advantages:

- the voltage distribution across the winding is correct;
- the measurements are made at operating temperature;
- normal mechanical forces are present.

The first condition reduces the risk of obtaining overly pessimistic PD results on the machine as it renders the measurement preferentially sensitive to the more highly electrical stressed areas of the winding. The second advantage is also extremely important because of the temperature dependence of PD in rotating machines as well as other insulating systems. In addition to the influence of temperature on void characteristics, temperature fluctuation is also known to have profound effects on PD behaviour through such mechanisms as:

- thermally induced differential axial expansion between the copper conductors and the insulation,
- radial expansion of the insulation in the case of thermoplastic insulation systems.

Consequently, it is important to ensure that the machine operating conditions remain substantially the same when tests are performed. However, in special cases it is very helpful for the analysis of the measured PD data to perform PD tests at various load points and temperatures, thereby being able to separate the different influences of temperature and vibrations due to electromagnetic forces acting on the winding. The principle operating parameters of relevance are:

- terminal voltage;
- real and reactive power;
- hydrogen pressure, if applicable;
- stator temperature, and
- stator current.

Guidance with respect to the tolerances expected of these parameters is provided in IEEE 1434-2000. The ability to perform PD tests in the presence of the operating stresses is the major advantage of on-line techniques over their off-line counterparts. While off-line tests, when properly performed, analysed and interpreted can provide valuable insight into insulation condition, some uncertainty remains because generally the temperature is significantly different and there are no electromagnetic bar forces. For this latter reason, off-line PD testing cannot determine whether the winding is loose, unless the abrasion of the semiconductive armour resulting from the relative movement between coil/bar surface and core iron is very severe.

There are however, some disadvantages to on-line PD measurement techniques. These are:

- electrical interference;
- volume of data, and
- interpretation.

The first of these disadvantages, the problem of electrical noise, has been discussed extensively elsewhere. Volume of data can become a problem for manufacturers and users monitoring large numbers of machines, even in situations in which the testing intervals are several months apart. This problem is further aggravated when using continuous on-line techniques. The obvious answer is to use some form of data compression or alarm processing, which is derived from specific PD data trending procedures, so that only deviations from the norm are considered worthy of further attention. Techniques such as artificial neural networks and expert systems are, in principle, suited to this task. Unfortunately, with the present understanding of the causes, mechanisms and effects of PD, it is difficult to fully define the decision points necessary for such automation. Clearly, further work is required in this area before reliable systems can be expected. Similar comments apply to data interpretation. While, there are some basic interpretation rules, which have also appeared in the literature, and a concerted CIGRE effort, has resulted in a document, CIGRE Technical Brochure 226 [2], that formalizes these rules, complete understanding of the significance of certain types of observed PD behaviour is still far away. Despite claims of success for statistical post-processing of PD data, automated interpretation that can provide the same level of confidence as the skilled and experienced observer is not yet a reality.

Annex B
(informative)

Non-electrical methods of PD detection and methods for localization

The following given methods are non-comparable and non-quantifiable.

a) Visual detection

Dark room (black-out) test with a.c. voltage: a method of determining the presence and location of surface discharges.

b) Optical detection

Ultraviolet detection equipment: See a).

c) Acoustic detection

AC voltage test in silent environment: location by the naked ear or an acoustical wave-guide (with flashover protection) for example insulated stethoscope. Note that it is not normally possible to detect PD activity in the groundwall insulation with acoustical methods unless the activity is especially great.

d) Ultrasonic detection

Ultrasonic detection equipment: See c).

e) Ozone detection

The presence of surface discharges causes chemical reactions. One of the by-products of the chemical reactions is ozone that has a characteristic smell.

Annex C
(informative)

External noise, disturbance and sensitivity

C.1 General

Noise and disturbances may be defined as any part of the observed electrical signal that is unwanted. The nature of PD measurements requires that noise be classified as inherent noise in the measuring instruments and that which is due to external disturbances. External disturbances due to constant wave signals or pulsed interference signals can occur either as conducted or irradiated signals. There is a close link between sensitivity, noise and disturbances. Therefore, it is impossible to discuss one of these topics without dealing with the other two topics at the same time. Since the person who has to perform off-line tests on site or during factory tests has usually a given measuring device, the following clauses will be limited to basic problems and how to deal with them.

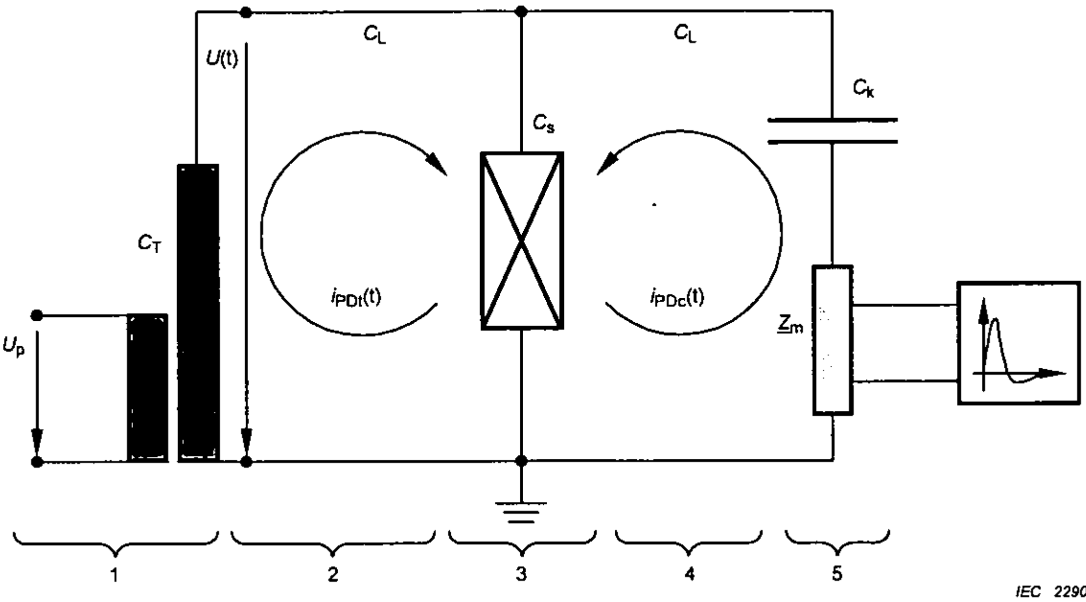
C.2 Sensitivity

The sensitivity of a PD measuring device can roughly be defined by the ratio of the real PD energy, at the PD location, to the energy that reaches the PD detector and is measured there.

At the time a PD occurs, the whole test arrangement (Figure C.1) with its capacitances including transformer (i_{PDt}), power lines (i_{PDl}), the PD coupling unit (i_{PDc}) and the test sample (i_{PDs}) itself, recharges this PD location. Obviously, the sum of all of these current components is equal to the resulting current at the PD location: $i_{PD} = i_{PDt} + i_{PDl} + i_{PDs} + i_{PDc}$.

Consequently, the ratio $i_{PDc}/(i_{PDt} + i_{PDl} + i_{PDs})$, i.e. the charge displacement on the coupling capacitor, reflects the sensitivity of the measurement and thus, the higher the capacitance of the PD coupling unit and thus the ratio of coupling capacitance to the test object capacitance, the higher is the sensitivity of the measurement.

Therefore, if one is free to choose the coupling capacitor, the highest sensitivity can be expected with a coupling capacitor having a large capacitance. At least, the coupling capacitor needs to fit well to the band pass characteristic of the measuring equipment and to the measuring impedance $\underline{Z}_m$.



Key

1 transformer, auxiliaries

2 line

3 sample

4 line

5 coupling device

$U(t)$	test voltage (transformer secondary voltage)
U_p	transformer primary voltage
C_L	power line stray capacitance
C_s	sample capacitance
C_T	transformer stray capacitance
$i_{PDt}(t)$	transient PD current over transformer path
$i_{PDc}(t)$	transient PD current over the coupling unit path

Figure C.1 – Recharging of the test object by various current components

C.3 Noise and signal-to-noise ratio

The total noise in an electronic system results from two distinct types of noise: fundamental noise and excess noise. Fundamental noise arises from the motion of discrete charges in electrical circuits and cannot be completely eliminated. Excess noise arises from imperfect instrumentation or non-ideal component behaviour and can in principle be reduced to insignificant levels. Both types of noise, in principle, display frequency independent magnitudes. Since the excess noise is mainly influenced by instrument design, it can only poorly be influenced and reduced by personnel taking PD measurements and is therefore not further discussed.

The main fundamental noise is the thermal noise (Johnson noise) that is caused by thermal movement of discrete charges. Across a resistance these thermal fluctuations of the charge carriers lead to a voltage drop that appears as external noise across such components. Obviously, the noise level increases with temperature (faster thermal movement) and with the resistance (higher voltage drop).

Since all PD measuring systems, compliant with IEC 60270, work in principle with quasi-integration-filters, the bandwidth of the measuring device leads to the same behaviour for signal and noise: the larger the bandwidths, the more signal energy will be detected. Therefore the output signal of such an integrator will increase with increasing bandwidth, resulting in higher output signals for the wanted PD signal and the noise signal as well. However, in contrast to the amplitude frequency spectrum of the wanted PD signal, which is constant up to very high frequencies, the thermal noise spectrum decreases with increasing frequency.

Since the output signal of a band pass filter is proportional to bandwidth for a PD pulse and proportional to the square root of the bandwidth for thermal noise, the signal-to-noise ratio SNR rises roughly with the square root of the bandwidth – the higher the bandwidths, the higher the SNR.

The relations described in the last paragraph are valid for a given PD coupler with a fixed resistive measuring resistance. Such a configuration leads to fixed lower cut-off frequency and is therefore valid for one special arrangement. To reduce the lower cut-off frequency, it is necessary to increase the coupling capacitance. Such larger couplers lead to larger currents through the sensor and therefore to higher output signals. Therefore, devices operating in low frequency ranges with low bandwidths may have the same SNR as measuring devices operating in high frequency range with large bandwidths. At least the measuring device consisting of coupling capacitor, coupling impedance and the measuring device have to fit together.

C.4 Disturbances

We here distinguish between disturbances and noise by their nature. Disturbances appear sporadically or periodically and are from external sources, for example converters, voltage dips or nearby high voltage corona. During installation of the off-line measuring device, some measures have to be taken to reduce the negative effect of such disturbances. For off-line measurements some of these external signals are less dominant than for on-line measurements. Some general rules to reduce the influence of such external disturbance signals are given in 9.1.6.2.

Annex D
(informative)

Methods of disturbance suppression

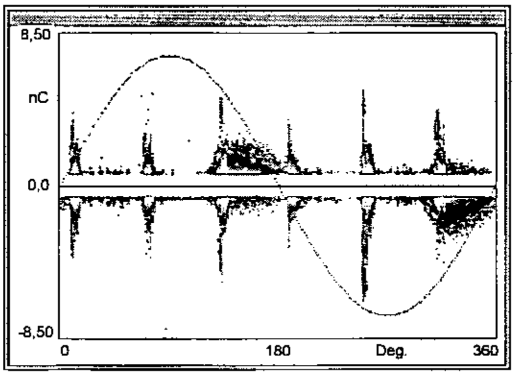
D.1 Frequency range limiting

The idea behind this method is, that the frequency spectra of external disturbances (interference noise) do not show a continuous frequency spectrum in the way described in Figure 1 for PD pulses.

For reducing the influence of such disturbances to the measurement circuit, narrow band systems (5.4) with bandwidths between 9 kHz and 30 kHz can be used. When shifting the centre frequency between the highest disturbances the influence will be significantly reduced. The measuring device can be matched to the test arrangement.

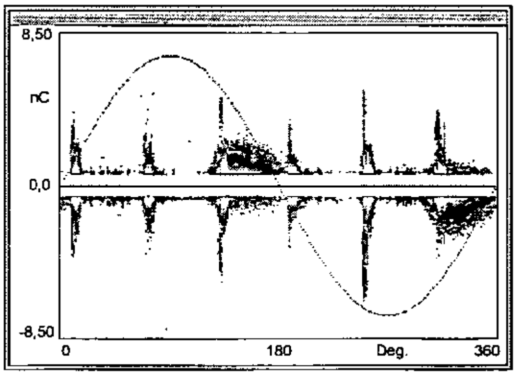
D.2 Phase window masking

Phase stable disturbances can be eliminated by fading them out (Figures D.1 and D.2). This can be done electronically by disabling the measuring channel during pre-defined phase windows. The user should be aware that both, disturbances and PD from the test object are masked and that the data are irretrievably lost.



IEC 2291/06

Figure D.1 – Without window masking



IEC 2292/06

Figure D.2 – With window masking

D.3 Masking by noise signal triggering

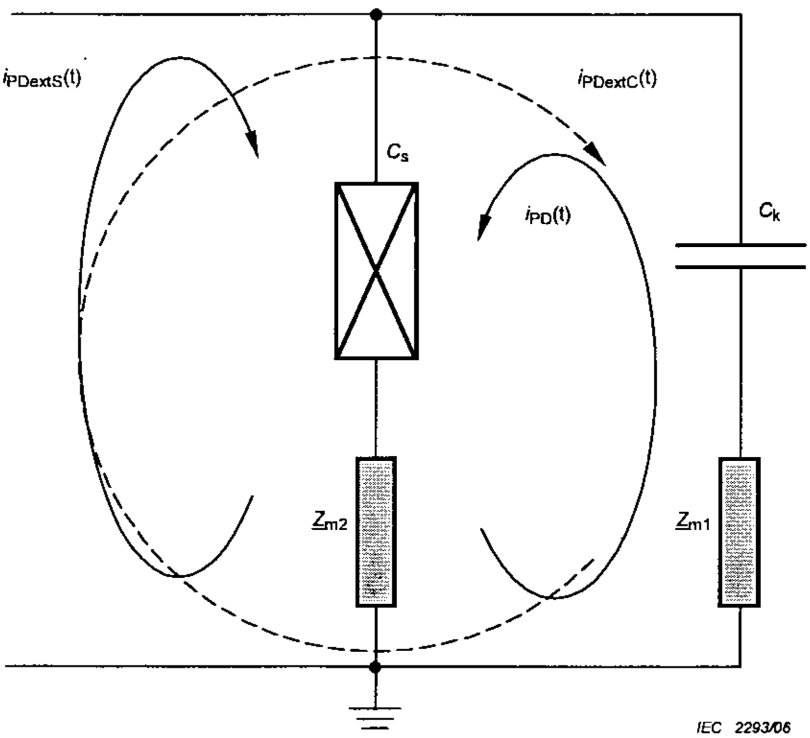
The PD measuring device must be equipped at least with two input channels: besides the measuring channel, a second measuring channel, operating as a gating channel, is necessary. If this second channel receives a signal, the measuring channel will be disabled for a certain time. Therefore, the PD sensor of the gating channel has to be adjusted thoroughly to the source(s) of disturbance.

D.4 Noise signal detection by measuring the propagation time

The PD pulse propagates as a wave through the test object and the cabling. Therefore, the pulse reaches different locations in the test object and the cabling at differing times. When installing two PD couplers at various locations, the direction of the pulse can be registered. External PD signals as well as external disturbances can then be separated from the PD signals coming from the test object. If external disturbances are cross-coupled to the test object they will be handled as PD from the test object.

D.5 Two-channel signal difference method

Since both external signals and PD from the insulation propagate through the test sample and through the PD coupling device, they can be measured at both locations.



Key

C_s sample capacitance

C_k coupling capacitor

$\underline{Z}_{m1}$, $\underline{Z}_{m2}$ coupling device (measuring impedance)

$i_{PD}(t)$ PD current due to PD in the test object

$i_{PDextC}(t)$ PD current in the coupling unit path due to external PD

$i_{PDextS}(t)$ PD current in the sample path due to external PD

Figure D.3 – Pulse currents through the measuring circuit

Obviously, the voltage drops across both measuring impedances have the same polarity for external sources and opposite polarities for PD from the test object itself (see Figure D.3).

Two optional ways of connecting the measuring device to the low voltage coupling devices (measurement impedances) are possible.

First a measuring device with two inputs, one for each coupling device, measures the voltage drops individually. With the polarity information, the external signals can be faded out afterwards.

The second way is to connect the measuring device between the upper connections of the measuring impedances. When assuming same measuring impedances and no phase shift of the currents through the two circuits the measured voltage difference is about zero for external signals or disturbances and is doubled for PD coming from the test object.

D.6 Suppression of constant wave (CW) signals by digital filtering

Constant wave signals are narrow band sinusoidal noise signals, for example caused by the carrier frequencies of radio stations. A powerful method to suppress constant wave noise is the use of high order digital filters, which are adjusted to reduce the noise at different frequency bands, at which constant wave noise is present. These filters are implemented within digital PD measuring devices as signal processing algorithms. Compared to frequency range limiting with narrow band PD measuring systems (see Clause D.1), the advantage of digital filtering is the higher energy content of the PD signal that can be detected from the winding, resulting in a higher signal-to-noise ratio. In addition, the information on pulse polarity is preserved.

To reduce the unwanted signals, their frequencies should be known. Therefore, this method requires the analysis of the detected signal in the frequency domain. The determination of the filter coefficients is performed by analysing the noisy environment in the frequency domain to detect and weight the noise frequency regions for subsequent fade-out. Thus, the optimal digital filter design depends on the individual environment, in which the PD test is performed.

During the actual PD measurement, the detected signals are then processed in accordance with the specific filter characteristics.

D.7 Noise rejection using signal processing techniques

Pulsed noise can be due to several sources in a power plant, for example corona discharges (PD outside the test object) or pulses due to power electronic devices like machine exciters.

Pulsed noise rejection can be obtained by analysing the digitized pulse shapes. Indeed, PD and noise pulses are usually different in shape, thus in frequency spectrum, due to the nature of the source and of the transfer impedance between the pulse source and the detector input. As an example, pulses due to the exciter have usually a lower frequency content than PD pulses originating from the insulation system.

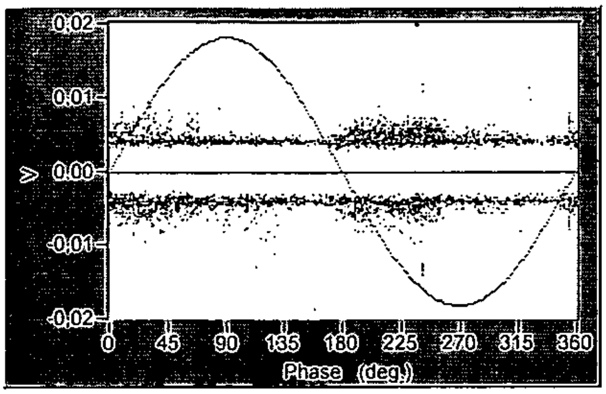
This approach requires a suitable hardware which is capable of capturing the pulse shape for each single PD event (i.e. providing sufficient bandwidth, sampling rate and acquisition memory, capable of acquiring pulses on the basis of trigger conditions and with small dead time) and appropriate software tools. To reduce the effect of continuous, additive noise, the detector frequency response can be profiled using appropriate filters.

By classifying each recorded pulse in accordance with some characteristic parameters, for example bandwidth, pulse shape, decay characteristics, etc. it may be possible to separate PD in the test object from noise pulses and to assign each single pulse to a certain PD source category or location. Such a classification may then also be used efficiently to analyse each detected PD source separately, for example for trend evaluation.

A general procedure for the separation of PD pulses from noise pulses may be the following:

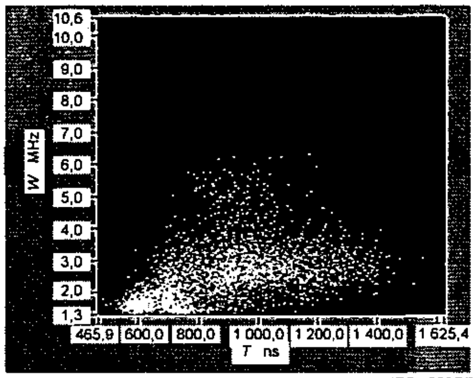
- record a sufficiently-large number of pulses;
- from each recorded pulse, extract some features which can outline the differences between PD and noise pulses;
- group pulses having similar features together;
- for each group, evaluate a phase resolved PD pattern;
- discard those pulses which give rise to phase resolved PD patterns undoubtedly associated with noise; this procedure can be automatic or on the basis of operator experience.

In Figures D.4 and D.5, two examples are shown for a pulse classification in accordance with their equivalent timelength T and bandwidth W. The definition of these parameters can be found in standard textbooks on telecommunication theory.



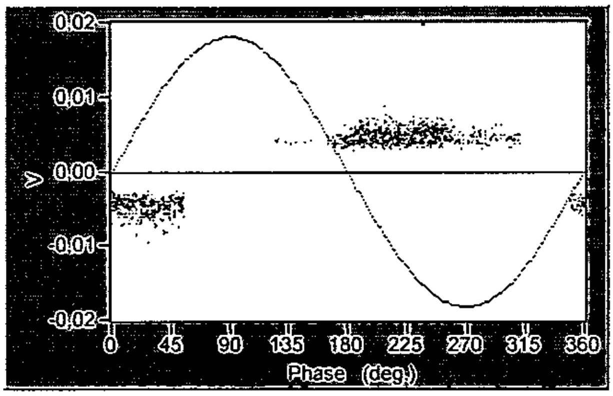
IEC 2294/06

Figure D.4a – Complete acquisition pattern



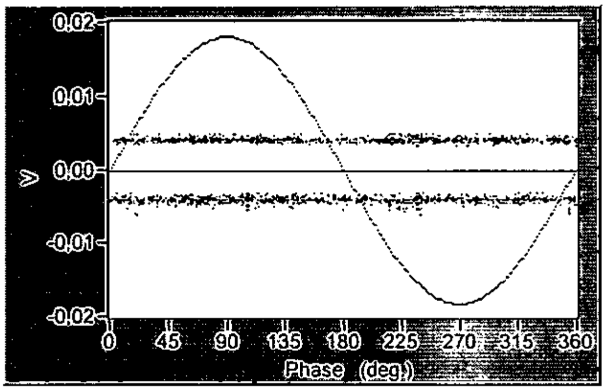
IEC 2295/06

Figure D.4b – Time/frequency map of recorded pulses



IEC 2296/06

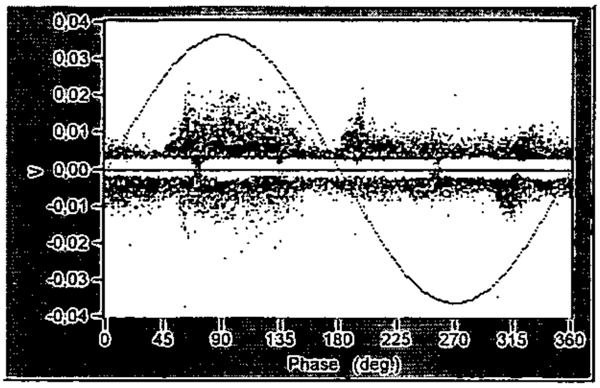
Figure D.4c – Sub-pattern 1, red cloud: internal discharges



IEC 2297/06

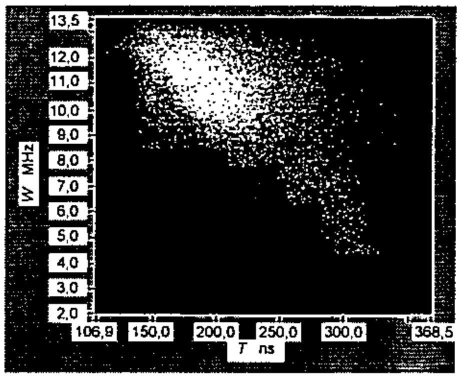
Figure D.4d – Sub-pattern 2, white cloud: uniformly-distributed noise

Figure D.4 – Example of noise rejection



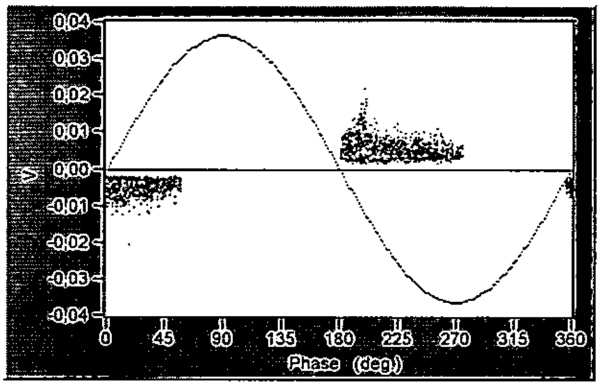
IEC 2298/06

Figure D.5a – Complete acquisition pattern



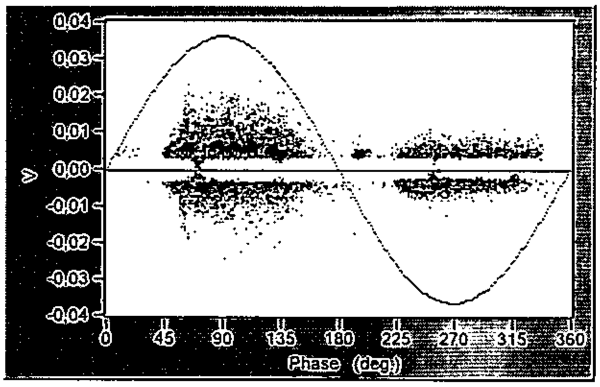
IEC 2299/06

Figure D.5b – Time/frequency map of recorded pulses



IEC 2300/06

Figure D.5c – Sub-pattern 1, white cloud: internal cavity discharges



IEC 2301/06

Figure D.5d – Sub-pattern 2, red cloud: cross-talk

Figure D.5 – Example of cross-talk rejection

Annex E
(informative)

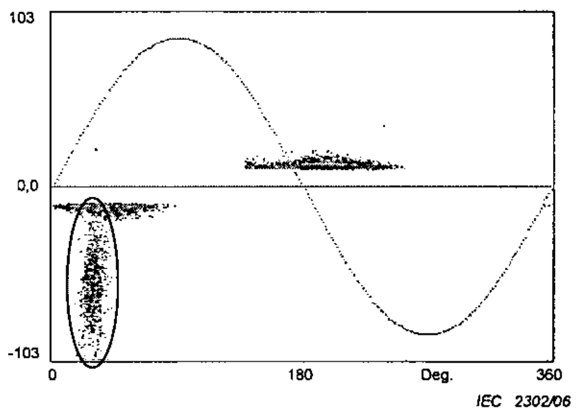
Interpretation of PD magnitude data and phase resolved PD patterns

E.1 Instructions for interpretation of PD patterns

E.1.1 Example PD patterns

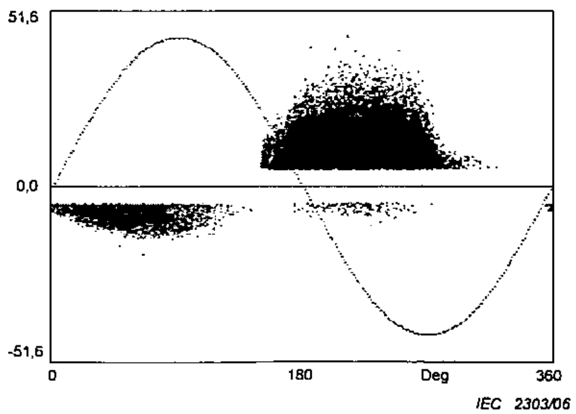
The following measurements were taken under well-controlled laboratory conditions [5], so that the PD processes are well-known. The phase resolved ϕ-q-n patterns may give an impression of possible PD patterns that can be measured and that can be displayed when using appropriate measurement equipment. Superposition of patterns is possible, also variation in pattern shape, PD frequency or other characteristics. Different patterns than shown here may occur for different PD sources.

The PD patterns shown here (Figure E.1) were measured with the low voltage coupling device placed on the ground side of the coupling capacitor in accordance with Figure 5a.



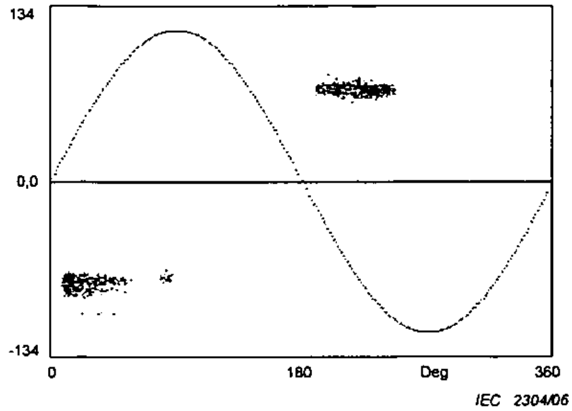
End-winding discharges

Surface discharges/tracking along the winding overhang due to contamination at the air/insulation interface



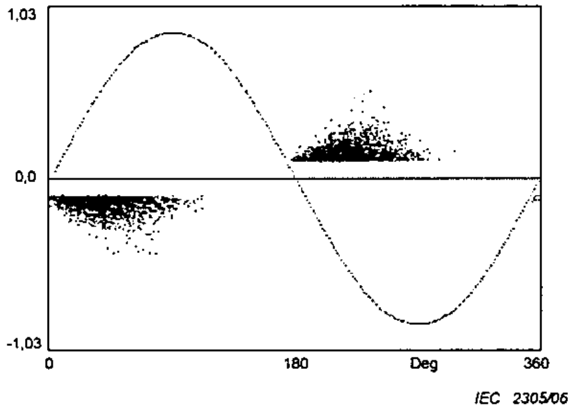
End-winding discharges

Discharges at the junction of the conductive slot coating and the stress control coating due to inadequate interface properties



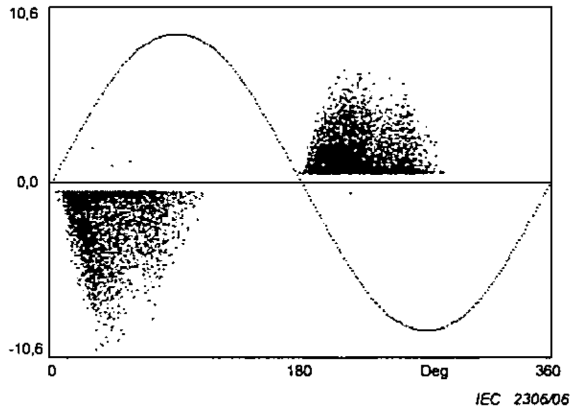
End-winding discharges

Gap type discharges between bars in the winding overhang or between a bar and the press finger of the core



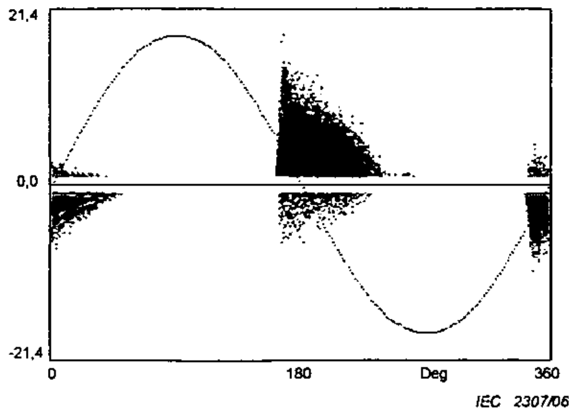
Internal void discharges

Discharges from internal voids within the main insulation



Delamination discharges

Discharges from delamination between the main insulation and the copper conductor



Slot discharges

Slot discharges in the air gap between the laminated stator core and the side of the stator bar

Figure E.1 – Example PD patterns

E.1.2 Basic risk assessment

Table E.1 refers to Clause 4 (Nature of PD in rotating machines) and will give some basic ideas with regard to the risk associated with some major PD sources.

The risk assessment given is based on experience with modern resin impregnated mica tape based high voltage insulation systems and may vary in dependence on the insulation material, the location of the PD source, surface conditions, etc.

Table E.1 – Risks associated with the main PD sources in rotating machines

PD source	Risk	Remarks
Internal voids 4.2.2.1	Low	Inner (internal) PD's are generated within air or gas filled pockets that are embedded within the main insulation. They result from the manufacturing process and do not indicate ageing factors. Under normal circumstances, internal discharges do not lead to remarkable ageing
Internal delamination 4.2.2.2	High	Internal delamination PD's are generated within air or gas filled elongated pockets (in longitudinal direction) that are embedded within the main insulation. They often result from overheating or from extreme mechanical forces that both lead to separation of large areas between insulation layers
Delamination between conductors and insulation 4.2.2.3	High	Delamination PD's between conductors and insulation material are generated within air or gas filled elongated pockets (in longitudinal direction) that are embedded between the main insulation and the field grading material. They often result from overheating or from extreme mechanical forces that both lead to separation of large areas between these layers
Slot discharges 4.2.3	High	Slot discharges are generated by poor, or missing, contact between the field grading layer and the stator slot wall. Typically, these discharges appear only during operation of the machine. Electromechanical forces and vibration lead to contact arcing that can be measured as slot PD. Only in case of large degradation of the field grading layer such slot discharges can be measured off-line, and than they can be characterized as the PD source explained in 4.2.3
End-winding and surface discharges 4.2.4	Normal	End-winding and surface PD's are generated somewhere on the surface of the insulation material and therefore are located normally in the end-winding section of a machine. They result often from conductive contamination (carbon, oily dust, abrasion, etc.) or from damaged field grading materials. Since surface discharges only appear on the surface of the insulation they normally do not lead to significant ageing. However, in the presence of other factors such as high ozone concentration or surface contamination, ageing can be accelerated
Conductive particles 4.2.5	Normal	PD's from conductive particles are generated somewhere on the surface of the insulation material and therefore are located normally in the end-winding section of a machine. They result often from large areas of conductive contamination (carbon, oily dust, abrasion, etc.) or from separated regions of field grading materials. Since they only appear on the surface of the insulation they normally do not lead to significant ageing. However, in the presence of other factors such as high ozone concentration or surface contamination, ageing can be accelerated

E.1.3 Basic magnitude assessment

Such an assessment is impossible without knowing the real PD location. For example, surface PD may be ten or hundred times higher than internal PD or PD from delamination, without indicating ageing phenomena that lead to premature insulation failure. Whereas, for example the presence of delamination processes, independent of the measured PD amplitudes, indicate rapid ageing that needs to be repaired promptly.

Bibliography

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[5] HUDON, C.; BÉLEC, M.: *Partial Discharge Signal Interpretation for Generator Diagnostics. IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 12, No. 2, pp. 297-319, 2005

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