IEC/TS 60034-27-2

Edition 1.0 2012-03

TECHNICAL SPECIFICATION

colour inside

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

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

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ROTATING ELECTRICAL MACHINES –

Part 27-2: On-line partial discharge measurements on the stator winding insulation of rotating electrical machines

FOREWORD

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

IEC/TS 60034-27-2, 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
2/1636/DTS	2/1649/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.

NOTE A table of cross-references of all IEC TC 2 publications can be found on the IEC TC 2 dashboard on the IEC website.

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

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- withdrawn,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

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

For many years, the measurement of partial discharges (PD) has been employed as a sensitive means of assessing the quality of new insulation as well as a means of detecting localized sources of PD in used electrical winding insulation arising from operational stresses in service. Compared with other dielectric tests (i.e. the measurement of dissipation factor or insulation resistance) the differentiating character of partial discharge measurements allows localized weak points of the insulation system to be identified. Especially on-line PD measurements are not only sensitive to partial discharges but also to various arcing and sparking phenomena.

With regard to condition assessment of rotating machines, the measurement of partial discharges can provide information on:

– points of weakness in the insulation system;
– degradation processes;
– maintenance 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 a 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 detailed discussion of PD off-line testing is provided in IEC/TS 60034-27, whereas this technical specification is confined to on-line techniques. The approach to deal with PD on- and off-line measurement techniques in two different technical specifications is considered necessary to render each specification sufficiently concise to be of use by non-specialists in the field of PD measurement.

PD on-line measurements are recorded with the rotating machine experiencing all of the operating stresses; thermal, electrical, environmental and mechanical. On-line PD testing has the following advantages:

– the voltage distribution across the winding is the same as during operation;
– the measurements are made at operating temperature;
– normal mechanical forces are present.

Due to the realistic stress impact on the winding during measurement and due to the fact that the measurement is performed during normal operation, on-line PD testing has become very popular. Since no service interruption is required, once the PD sensors are installed during a scheduled unit outage, and no external power source is needed, on-line testing is usually cost effective compared to off-line PD measurement. Condition changes of the stator winding insulation system can be identified and evaluated at an early stage based on a real-time condition assessment and thus condition-based and predictive maintenance strategies can be improved.

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 measuring equipment, are recommended to ensure reliable assessment of the condition of the stator winding insulation.

This technical specification does not deal with online PD measurements on converter driven electrical machines because different measuring techniques are needed to distinguish between noise from the converter and PD from the winding. For this purpose IEC/TS 61934 may apply.

Limitations

On-line PD tests on stator windings produce comparative, rather than absolute measurements. This creates a fundamental limitation for the interpretation of PD data, and implies that simple limits for allowable PD cannot be established unless many precautions are taken. For the same reasons, PD acceptance criteria for new or rewound stator windings cannot be established unless many precautions are taken. The reasons for the difficulty to set absolute limits for PD include:

- There are many types of PD sensors as well as recording and analyzing instruments. Generally they are incompatible and will produce different results for the same PD activity.
- Even with the same measuring system, partial discharges will interact with the winding capacitance, inductance and/or surge impedance to produce different voltage and current pulses. Thus PD measurements from machines with different ratings and/or winding connections may produce different PD results, even though the actual amount of damage may be the same.
- Different types of defects can produce different PD magnitudes, even with the same amount of damage.
- PD may occur close or far from the PD sensor. In general if the PD is physically far from the PD sensor, it will produce a smaller response at the PD sensor due to attenuation.

Users should also be aware that there is no evidence that the time to failure of the stator winding insulation can be estimated using any PD quantity, even in combination with other electrical tests. Also, determining the root cause of an insulation deterioration process using pattern recognition, especially if more than one process is occurring, is still somewhat subjective, although the technology is evolving rapidly.

Noise and disturbance may have a great impact on the detected signals, especially for on-line PD measurements. Cross-coupling of PD and noise on one phase can obscure PD on another phase. With some measuring systems, this can make objective interpretation of the test results difficult.

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 pulse-less discharge phenomena.

ROTATING ELECTRICAL MACHINES –

Part 27-2: On-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 the installation;
– normalization and sensitivity assessment;
– measuring procedures;
– noise reduction;
– the documentation of results;
– the interpretation of results;

with respect to partial discharge on-line measurements on the stator winding insulation of non-converter driven rotating electrical machines with rated voltage of 3 kV and up. This technical specification covers PD measuring systems and methods detecting electrical PD signals. The same measuring devices and procedures can also be used to detect electrical sparking and arcing phenomena.

NOTE The main differences between on-line measurements and off-line measurements are due to a different voltage distribution along the winding and various thermal and mechanical effects related to the operation, like vibration, contact arcing or temperature gradients between stator copper and stator iron core. Furthermore, especially for hydrogen-cooled machines the gas and the gas pressure is different for off- and on-line PD measurements.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

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

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 1 to entry: 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
periodic on-line PD measurement
on-line PD measurement performed on the machine at regular intervals

3.4
continuous on-line PD measurement
on-line PD measurement performed on the machine with a measuring device continuously acquiring PD data

3.5
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 1 to entry: 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.

3.6
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 1 to entry: This coating together with adequate slot design provides electrical contact to the stator core, without shorting the core laminations.

3.7
corona discharge
visible partial discharge adjacent to the surface of a conductor in gases

3.8
slot discharges
discharges that occur between the outer surface of the slot portion of a coil or bar and the grounded core laminations due to high voltage

3.9
vibration sparking
interrupted surface currents between the outer surface of the slot portion of a bar and the grounded core laminations due to axially induced voltages on the conductive slot coating combined with bar vibrations

3.10
internal discharges
discharges that occur within the insulation system

3.11
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

3.12
pulse magnitude distribution
number of pulses within a series of equally-spaced windows of pulse magnitude during a predefined measuring time

3.13
pulse phase distribution
number of pulses within a series of equally-spaced windows of phase during a predefined measuring time

3.14
phase resolved 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

3.15
PD sensor
general type of transducer, which can be used to detect PD signals from the machine winding

Note 1 to entry: A PD sensor typically consists of a high voltage coupling capacitor of low inductance design and a low voltage coupling device in series.

3.16
coupling device
usually an active or passive four-terminal network that converts the input currents to output voltage signals

Note 1 to entry: These signals are transmitted to the measuring device 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 device.

3.17
resistance temperature detector
RTD
temperature detector inserted into the stator winding, usually between the top and bottom bar or between embedded coil sides in a given slot

3.18
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 a specified number of pulses per second, which can be directly inferred from a pulse magnitude distribution.

Note 1 to entry: A recommended pulse repetition rate is 10 pulses or more per second.

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 is not a total breakdown of the insulation system. PD in general requires a gas volume to develop, e.g. 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 exceeds the dielectric strength of the insulating material. 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, e.g. 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 or failure probability may not always correlate with PD levels, but depends significantly on other factors, for example operating temperature, wedging conditions, bar vibrations, 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.

The main differences between on-line measurements and off-line measurements are due to a different voltage distribution along the winding and various thermal and mechanical effects related to the operation, like vibration, contact arcing or temperature gradients between stator copper and stator iron core. Furthermore, especially for hydrogen-cooled machines the gas and the gas pressure is different for off- and on-line PD measurements.

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 existing 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. For example in a resin impregnated mica tape insulation system, that is commonly used in high voltage rotating machines, 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

Thermal cycling may cause delamination at the interface of the conductor and the main insulation. This delamination can result in partial discharges which can relatively rapidly result in failure especially in multi-turn coils.

4.2.2.4 Electrical treeing

Electrical treeing in machine insulation is an ageing process in which fine erosion channels propagate through the epoxy around the mica barriers and may finally lead to electrical breakdown of the main insulation. Electrical treeing can start at any point of locally enhanced electric field within the insulation, e.g. rough structures of the inner conductor, insulation impurities, gas filled voids or delaminations in the insulation. This process is associated with internal partial discharge activity.

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. Higher 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. Slot discharges are generally caused by locally enhanced electric fields, and thus these processes occur only at the higher voltage end of each phase. The absolute time between detection of this phenomenon and final insulation failure is generally unknown. However, compared to other typical deterioration effects this time could be relatively short, especially in the presence of bar/coil vibrations. Thus, reliable detection at an early stage is necessary to decide if appropriate remedial actions are required.

4.2.4 Discharges in the end-winding

4.2.4.1 General

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.

4.2.4.2 Surface discharges

Surface discharges generally occur whenever the electrical field along a surface exceeds the breakdown field of the surrounding gas. This may occur if no stress control coating is applied or the stress control coating of the end-winding becomes ineffective because of poorly designed interfaces, contamination, porosity, thermal effects, etc. When reliable field grading is no longer assured 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. Surface discharges usually result in a phase to ground fault.

4.2.4.3 Phase to phase discharges

PD may occur between phases, for example due to inadequate phase to phase clearances or at elements of the overhang support system like spacers or cords. Depending on specific design details these discharges may have large magnitudes and may either occur as surface discharges or internal discharges and thus the time between detection of this phenomenon and final insulation failure is uncertain. Phase to phase discharges may result in a phase to phase breakdown.

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 Arcing and sparking

4.3.1 General

In contrast to the types of PD described in 4.2, which are caused by locally enhanced electric fields, arcing and sparking phenomena occur due to interruption of currents resulting from the magnetic flux within the stator core. These processes involve higher energy and temperatures, which leads to a faster degradation of the insulation materials. Arcing and sparking lead to transient pulses, which can also be detected by PD measuring systems.

4.3.2 Arcing at broken conductors

Broken conductors, resulting from mechanical vibrations, may lead to intermittent contacts and consequently to arc formation.

4.3.3 Vibration sparking

Due to the magnetic field in the stator core parasitic surface currents will flow axially along the conductive slot coating of a bar. In case the bar vibrates, these currents may be interrupted at a contact point to the core iron, and the interruption of this current will form an arc to the core. If the resistance of the conductive coating is too low, the current will be of significant magnitude and the resulting arc can damage the groundwall insulation by an erosion process. This so called vibration sparking, which is a relatively fast deterioration mechanism, may occur at any point of the winding and thus also at low potential sites, for example close to the neutral of the winding.

5 Noise and disturbance

5.1 General

An important challenge with on-line PD measurement is separating stator-winding PD from electrical noise or disturbances. In contrast to properly set-up off-line PD tests, in most online tests electrical disturbance pulses will often be present, and these disturbance pulses may be more frequent and of larger magnitude than the stator winding PD pulses, also the signals may be phase-locked to the AC power frequency voltage. If the disturbances are not adequately suppressed, or the test technician is not able to adequately identify what is a disturbance and what is stator PD, there is a great risk that the disturbance will be classed as stator PD. Consequently the stator may be identified as having serious insulation problems, when in fact the insulation may be in good condition. If too many 'false positives' occur, confidence is lost in the test, and future testing may not be routinely done, losing the benefit of online PD testing.

5.2 Noise and disturbance sources

Consistent with IEC/TS 60034-27, noise is defined to be non-stator winding signals that clearly are not pulses. Noise may be due to electronic devices within the PD detection system itself, for example thermal noise from semiconductive devices. Noise can also be from radio stations, radio transmitters, mobile telephones, power line carrier signals, etc. This noise is easily separated from pulse-like signals either visually on an oscillographic display or with the use of filters. Thus it is not considered further in this technical specification.

Disturbances are electrical pulses of relatively short duration that may have many of the characteristics of stator winding PD pulses – but in fact are not stator winding PD. Some of these disturbances are synchronized to the AC cycle, and some are not. Sometimes synchronized disturbance pulses can be suppressed based on their position with respect to the AC phase angle.

Examples of synchronized disturbances are:

a) Partial discharges caused by e.g. electrostatic precipitators or bushing discharges
b) Power tool operation such as from arc welding and commutator sparking (may also be unsynchronized)
c) Transients caused by power electronics, for example converter fed motors or excitation systems. This disturbance may also be unsynchronized to the AC cycle
d) Poor electrical connections (leading to contact sparking) on the bus or cable connecting the rotating machine to the power system
e) Poor electrical connections elsewhere in the plant that lead to contact sparking
f) PD in other apparatus connected to the motor or generator terminals, for example output bus, power cable, switchgear and/or transformers
g) Arcing or sparking sources within the motor or generator, such as stator core lamination sparking

Examples of non-synchronized disturbances are:

h) Power tool operation (arc welding and commutator sparking)
i) Transients caused by power electronics, for example converter fed motors or static excitation systems
j) Slip ring sparking on the machine rotor
k) Overhead crane power rail sparking

All of these disturbances create electrical pulses that the unwary may confuse with stator winding PD. With disturbances d), e), f), and g), the operator normally wants to know if such activity is occurring, because it may indicate other problems (beyond stator insulation problems) that may lead to equipment failure. Thus some users may not class these examples as a disturbance, but rather as signals to be identified.

To reduce the risk of false indications of the stator winding insulation condition, many methods have been developed to help users to manually and/or automatically separate stator winding PD from disturbances. Many of the commercially available methods use one or more of the methods identified below.

5.3 Frequency domain separation

The Fourier transform of an individual PD pulse will contain frequencies from DC up to several hundred megahertz, if the PD sensor is in close proximity to the PD source. Many types of disturbances produce pulses, but the frequency content of the pulses at the PD sensor may be lower than stator winding PD. For example, sparking caused by poor electrical contacts or PD in other apparatus that is remote from the machine under test, often produce frequencies up to just a few megahertz. Thus one method of separating PD from disturbances is to use analogue or digital filters that preferentially respond to pulses in specific frequency ranges. The PD measuring system (sensor and detection electronics) will be described as having a lower cut-off frequency and an upper cut-off frequency. Typical frequency ranges for on-line PD measuring systems according to Clause 6 are in the high frequency range (HF: 3 MHz to 30 MHz), in the very high frequency range (VHF: 30 MHz to 300 MHz), or in the ultra high frequency range (UHF: 300 MHz to 3 GHz). When using measuring systems in the low frequency range (LF: below 3 MHz), the lower frequencies will be subject to the significant influence of power line carrier, converter fed motor switching and excitation system disturbances, which need to be suppressed.

Generally, the higher the upper cut-off frequency of the PD detection system, the greater will be the signal to noise ratio, and thus the lower will be the risk of false indications. However, the higher the lower cut-off frequency, then the lower is the likelihood of PD being detected that is remote from the sensor. Assuming the PD sensor is located at the high voltage terminals of the stator winding, a low frequency range PD system will be sensitive to PD in more coils than a high frequency range PD system. Note however that in on-line PD testing the coils near the high voltage terminal are the only ones likely to have high levels of PD activity, since the voltage is higher than for coils remote from the terminals. However, other sparking and arcing phenomena, which may significantly damage the insulation, can also be detected by PD measuring devices and can occur throughout the winding even at low potential sites close to the neutral.

5.4 Time domain separation

In some on-line PD monitoring systems, PD is separated from disturbances on the basis of time domain characteristics. Two types of time domain separation systems have been employed:

– Pulse shape analysis

– Time of pulse arrival

Both types can only be used with a high bandwidth detection system.

Pulse shape analysis is the time domain analogy of filtering. It is predicated on specific time domain pulse characteristics such as rise-time and decay-time. For example, a PD sensor located close to the source of the stator PD may result in a detected rise-time that is shorter than a specific time, whereas certain kinds of disturbances (types a) to k) in 5.2) may be characterized by a longer rise-time. Digital circuits can separate stator PD from such disturbance sources by measuring the rise-time. Generally, the further the PD or disturbance source is from the PD sensor, the longer will be the rise-time of the detected pulse, since series inductance and/or the travelling wave phenomena called dispersion (frequency dependent velocity) tends to suppress the higher frequency components of a pulse.

Disturbance suppression using the time of pulse arrival method requires at least two PD sensors per phase to be installed on bus or cable connecting the motor or generator to the power system. This method depends on the time it takes an individual disturbance or PD pulse to travel along the power cable or bus.

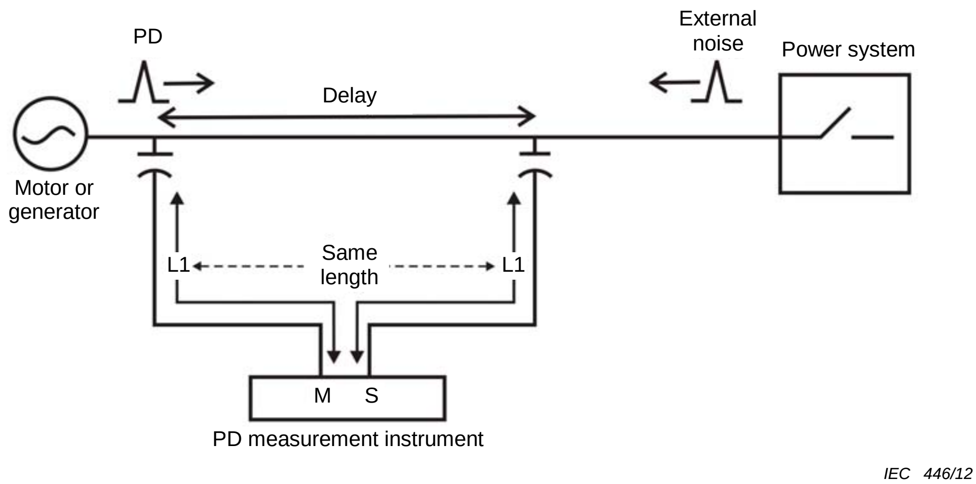


Figure 1 – Time domain disturbance separation by time of pulse arrival

As shown in Figure 1, pulses from the power system will arrive at “System” sensor (S) before it will arrive at the ‘Machine” PD sensor (M). The difference in the arrival time at each sensor depends on the distance between the two sensors, and the propagation velocity of the pulse along the bus or cable. Digital logic notes the relative time of arrival and categorizes the pulse as being from the power system, and thus assumed to be a disturbance. Similarly a pulse from the stator winding is assumed to be PD if the machine sensor detects the pulse before being detected by the system sensor. Note this separation method is only effective if the pulse arriving first at the machine sensor is stator PD, and not disturbances such as from slip ring sparking (type j) or other sparking within the machine (type g). Simultaneous measurements at the two sensors are needed.

5.5 Combination of frequency and time domain separation

Time and frequency domain characteristics can also be combined to separate disturbance pulses from stator winding PD. Time and frequency domain separation can be developed through a pulse shape analysis to produce a so-called “TF” map that plots the equivalent time length of the pulses versus their equivalent frequency content. The frequency content is normally calculated by a fast Fourier transform.

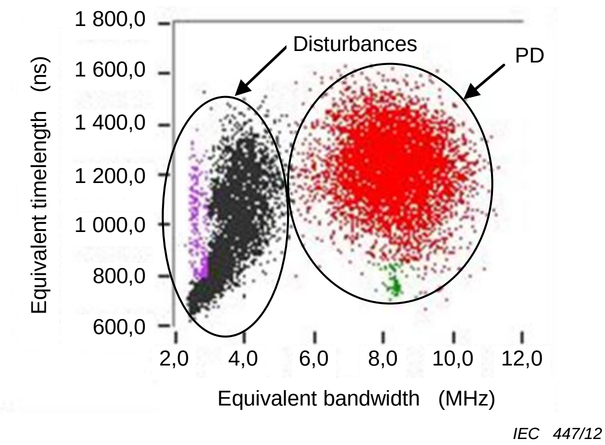


Figure 2 – Combined time and frequency domain disturbance separation (TF-map)

In a plot of the time domain versus frequency domain characteristics according to Figure 2 disturbances will often appear as a cluster of pulses that is in a position, which is distinctly different from stator winding PD, and can thus be identified and suppressed from the PD pattern.

5.6 Gating

Certain types of disturbances such as those from a static excitation systems (type c) produce disturbance pulses that are either phase-locked to the power frequency, or the timing of the disturbances can be obtained from an external source (such as a converter fed drive). In such cases, trigger circuits can be incorporated that predict when the disturbance will occur which then will open a gate to prevent the signal from the PD sensor at the time of the disturbance from being counted as stator PD.

For example, thyristor-based static excitation systems produce a disturbance from the commutation pulses, with a strong frequency component around 10 kHz. A filter which is sensitive to this 10 kHz component can be used to trigger a digital circuit that produces a “gate” signal whenever a thyristor pulse is detected. This gate signal can be used to prevent counting of any pulses that occur for the duration of the thyristor pulse. Some user knowledge is needed to set the trigger threshold and how long the gate is “open”. When the gate is “open”, legitimate PD pulses will also not be registered.

Gating can also be used to prevent radiated disturbances from being registered as PD. An antenna can be used to detect severe radiated disturbances. The antenna signal can be processed by filters and threshold detectors to produce a gate signal whenever a disturbance in certain frequency ranges above a set threshold occurs. Since this same radiated disturbance may also be detected by the PD sensor, the signal from the PD sensor can be interrupted whenever the gate is triggered. Some expertise is usually required to set the thresholds and since the disturbances transmission may change over time it is more appropriate for periodic monitoring systems.

5.7 Pattern recognition separation

Pattern recognition is the most fundamental means of separating PD from disturbance pulses. There are two basic approaches to pattern recognition: manual and automatic.

In the manual method, the output of the PD sensor is displayed for example on a digital oscilloscope or a purpose built PD instrument. The display may show the positive and negative pulses, the position of the pulses on the AC cycle, as well as the magnitude of the pulses (see Figure 8 in Clause 10). As described in Annex A, PD pulses occur in specific parts of the AC cycle, with particular polarity relationships relative to the AC cycle. Some types of disturbances will produce pulses that occur in different parts of the AC cycle, or will appear across the entire AC cycle. In addition they may have pulse polarity relationships that may be different from stator winding PD. An experienced observer can often recognize stator PD as a distinct pattern from various types of disturbances. Examples include static excitation interference (type c) that occur every 60 degrees across the AC cycle, and can easily be ignored by an observer of the display. Similarly, poor electrical contacts tend to produce pulses within a few degrees each side of the voltage zero crossings. Clearly, the more experience the observer has, the more likely that PD and disturbances will correctly be identified. This manual approach to pattern recognition is somewhat subjective, and different observers may come to different conclusions.

Automated (or computer-aided) pattern recognition is a rapidly evolving field of investigation. A number of pattern recognition methods have been applied to separate PD from disturbances and indeed separate various failure processes from one another. Some of the methods include:

– Statistical analysis of the distribution of pulses with respect to AC phase position, e.g. the mean, standard deviation, skew and kurtosis of the phase angle for positive and negative pulses. Stator winding PD will likely have different statistical moments than some types of disturbances.
– Artificial intelligence driven pattern recognition analysis to replicate the thought processes of an expert who manually distinguishes PD from disturbances.
– Time-frequency transforms, combined with cluster recognition methods and fuzzy logic to separate and to identify pulses associated with different failure processes and types of disturbances.

These and other computer-aided pattern recognition methods have found application to separate PD from disturbances in a more objective manner than can be obtained by manual methods. However the effectiveness of any particular method depends on the specifics of their implementation.

6 Measuring techniques and instruments

6.1 General

Generally, the measuring principles for partial discharges can be based on the energy conversion processes associated with the discharge, such as the emission of light, acoustic signals, electromagnetic waves, or formation of chemical reactions. However, this clause deals solely with electrical methods of measuring partial discharges because the electrical measurement of partial discharges is the most commonly used method of assessing the condition of the winding insulation of rotating machines. The electrical measurement can be carried out by using PD sensors detecting the conducted pulse signal components, or by using antennae detecting the electromagnetically radiated components of the pulse signals.

Partial discharge measuring systems can be divided into subsystems: PD sensor including the signal transmission system and measuring device, both of which significantly influence the PD measuring results. Selection of sensors, instrumentation and measuring technique is determined by the expected measurement parameters, which will be used for further analysis and interpretation of measurements.

6.2 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 location of the installed PD sensor differ from those at the point where it originates. With that in mind, the following points are very important for the measurement and subsequent interpretation of 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 cannot be measured directly;
– the individual high frequency transmission behaviour of a stator winding produces PD signals at the location of the installed PD sensor that are a characteristic of the machine being tested and of the location of the PD source;
– the very high frequency components of the 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 location of the PD sensor.

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 PD sensor and measuring device, will significantly influence the characteristics of the PD signal detected from the winding.

6.3 Signal transfer characteristics

Figure 3 shows schematically the frequency response of an idealized PD pulse at the origin of the PD within the winding (upper cut-off frequency f_{uPDo}) and the idealized frequency response at the terminals of the machine (upper cut-off frequency f_{uPDt}) after travelling from the PD source through the winding to the terminals. Due to considerable attenuation of very high frequency components, the upper cut-off frequency of the PD signal arriving at the terminals (f_{uPDt}) will be significantly lower than that (f_{uPDo}) of the original PD pulse.

The PD measuring system, including PD sensor, measuring leads and measuring instrument, shows band pass filter characteristics having specific lower and upper cut-off frequencies, mainly depending on the specific design of the PD sensor and the input impedance of the measuring device. In Figure 3 three examples a), b) and c) are shown for different frequency responses of PD measuring systems. For commercially available systems the cut-off frequencies, and thus the measuring bandwidth of the system, may vary over a wide range of frequencies. The characteristic frequency response of the complete measuring system has a considerable impact on the overall sensitivity of detection and the properties of the signal used for further analysis and interpretation.

It should be noted that Figure 3 only describes the fundamental relationships by showing idealized curves. Depending on the winding design and the measuring arrangement used, in practical cases there may be several effects that will influence the exact shape of the frequency response curves and therefore may also influence PD results, e.g. resonance phenomena in the frequency range of the PD measuring system, which are not shown here.

For PD on-line measurements on rotating machines the following typical frequency ranges for the complete PD measuring system can be defined:

a) In the **low frequency (LF) range** a typical bandwidth of about 1 MHz, or a few hundred kHz according to IEC 60270, is used, with lower cut-off frequencies of usually above 100 kHz and upper cut-off frequencies usually below 3 MHz. Measurement in that frequency range ensures good sensitivity not only for partial discharges in bars/coils close to the PD sensor but also for those that originate from further away in the winding. However, the low frequency range is severely subjected to noise and disturbance, which is especially present during on-line measurements (see 5.2). Therefore special procedures for noise and disturbance separation are needed.

A PD measuring system working in the low frequency range basically detects the constant part of the PD pulse frequency response, assuming the stator winding has no resonant frequencies in the measurement frequency range. Since the upper cut-off frequency of the detection bandpass is significantly lower than the upper cut-off frequency of the pulse frequency response, the detected PD pulses are directly proportional to the apparent charge of the PD current pulse (principle of "*quasi-integration*"). However, the pulse shape of the bandpass output signal is determined by the low frequency bandpass characteristics. Since the original shape of the PD pulse arriving at the sensor location is lost when using low frequency bandpass systems, a separation of disturbance signals by pulse shape analysis or time domain separation is limited.

b) In the **high frequency (HF) range** a typical bandwidth of 3 MHz to 30 MHz is used. The lower cut-off frequencies may also be tuned well below 1 MHz to ensure good sensitivity for PD throughout the winding. However, often lower cut-off frequencies above 1 MHz are used to efficiently suppress typical disturbance signals that are present in the low frequency range.

   PD detection in the high frequency range is less susceptible to noise and disturbance and can be efficiently used to characterize the PD pulses arriving at the PD sensor by their individual pulse shape and thus being able to discriminate between different PD sources according to their signal shape. In the case where the upper cut-off frequency of the detection system is well above the upper cut-off frequency of the PD signal arriving at the location of the PD sensor, the bandpass output signal will display the PD pulse shape but will no longer be directly proportional to the apparent charge of the PD pulse. Thus, PD results in the high frequency range are usually expressed in terms of voltage [mV]. Efficient methods of frequency and time domain disturbance separation can be applied according to Clause 5.

c) In the **very high frequency (VHF) range** a typical bandwidth of a few hundred MHz is used with lower cut-off frequencies of typically 30 MHz and upper cut-off frequencies up to the 300 MHz range. As shown in Figure 3 the frequency response of such systems shows a pronounced overlap with the frequency response of the original PD pulse and therefore measurements in the very high frequency range ensure a good sensitivity to signals originating closer to the PD sensor. The PD sensor should be installed at the high voltage terminals and thus close to the coils/bars experiencing the highest electrical stress within the winding. The very high frequency range also provides a good signal to noise ratio and is therefore less susceptible to noise and disturbance. Because the upper cut-off frequency of the detection system is well above the upper cut-off frequency of the PD signal arriving at the location of the PD sensor, the measured signal will display the PD pulse shape but will no longer be directly proportional to the apparent charge of the PD pulse. Thus, PD results in the very high frequency range are usually expressed in terms of voltage [mV].

   PD detection in the VHF range ensures a very short pulse resolution time since the shape of the original very short PD current pulse can be detected. Therefore, efficient methods of time and frequency domain disturbance separation such as time-of-pulse arrival, pulse shape analysis and TF maps can be applied according to Clause 5.

d) In the **ultra high frequency (UHF) range** lower cut-off frequencies of typically 300 MHz and upper cut-off frequencies of up to 3 GHz are used. PD sensors working in that frequency range are antennae, which detect electromagnetically radiated pulse signals. The signal energy detected by these sensors and thus the sensitivity of PD detection mainly depends on the specific location of the antenna, the distance between the antenna and the PD source and the bandwidth of the detection system. In general, the closer the antenna is located to the specific PD sources the better will be the sensitivity of PD detection.

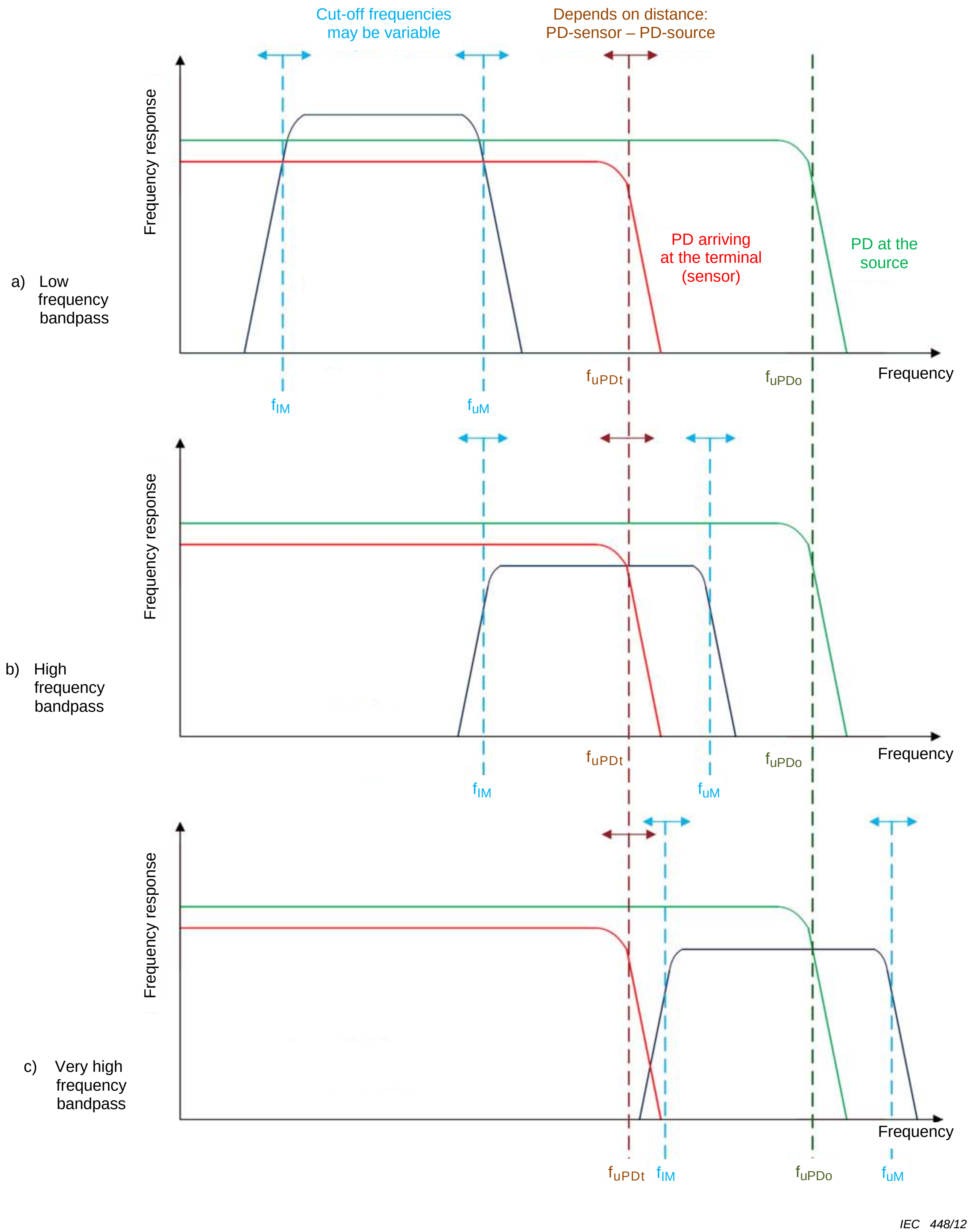


Figure 3 – Idealized frequency response of a PD pulse at the PD source and at the machine terminals; frequency response of different PD measuring systems: a) low frequency range, b) high frequency range, c) very high frequency range

NOTE The upper cut-off frequency of the PD arriving at the terminal (sensor) f_{uPDt} may significantly vary, depending on the distance between the PD sensor and the PD source. A small distance will result in a higher cut-off frequency, a large distance will result in a lower cut-off frequency due to attenuation phenomena.

Therefore in case b) and especially in case c) the measuring system shows good sensitivity to PD sources closer to the sensor, depending on the lower cut-off frequency of the bandpass filter and the overlap of the frequency responses of the bandpass filter and the PD signal at the sensor location.

6.4 PD sensors

6.4.1 General

In principle PD can be detected by conducted or electromagnetically radiated pulse signals. In the case of conducted PD signals a separate capacitance is used to detect the PD signal arriving at the location of the installed PD sensor. The electromagnetically radiated pulse signal is attenuated, due to various screening effects by machine components as iron core with slots, conductive coatings, etc. Thus the location of the antenna, the distance to the PD source and the specific bandwidth of the detection system significantly influence the detection sensitivity.

6.4.2 Design of PD sensors

PD sensors, which detect conducted pulse signals typically consist of a high voltage capacitance and a low voltage coupling device in series.

As separate capacitance the following arrangements can be used:

– existing surge capacitor;
– additional coupling capacitor;
– capacitance of connecting cables.

In order to form a PD sensor these capacitances can be used together with the following coupling devices, designed for an appropriate frequency response:

– RLC networks;
– current transformers including isolation transformers and Rogowski coils.

Depending on the specific design current transformers can be used on the low or high voltage side. Those PD sensors, which are designed to work in the low frequency range usually provide a 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. Whereas PD sensors that work in the very high frequency range provide a good sensitivity for PD close to the sensor.

PD sensors, which detect electromagnetically radiated pulse signals are typically antennae, which provide a characteristic sensitivity significantly depending on their place of installation and their specific frequency response function.

As PD sensors the following devices can be used:

– antennae specifically designed for PD measurements, such as stator slot couplers;
– slot RTD leads already installed in the stator winding;
– patch or microstrip antennae installed at specific locations of the machine housing.

PD sensors that act as antennae are usually designed to work in the very high and ultra high frequency ranges. These sensors need to be installed as close as possible to that part of the winding, which may be most exposed to critical PD activity.

It is recommended that the technical data sheet provided with the PD sensor should contain the frequency response curve of the PD sensor.

6.4.3 Reliability of PD sensors

PD sensors used for on-line PD monitoring are usually permanently installed on the machine. It is essential that the PD sensors themselves do not cause the failure of the stator winding. Normally inductive PD sensors such as used on the ground leads of power cables or surge capacitors will have no impact on stator reliability. Stator slot couplers and RTD leads mounted outside the PD suppression coatings or patch/microstrip antennae installed inside or outside the machine housing do not pose a risk. However, special purpose PD capacitors connected to the high voltage leads in a stator winding may pose a risk for a phase to earth fault. Thus such capacitive PD sensors should:

– have a PD extinction voltage (PDEV for a specified PD level of 10 pC) greater than two times the phase to ground operating voltage, verified by appropriate routine testing;
– be AC over-voltage routine tested to at least the same voltage as the stator winding;
– have undergone voltage endurance type test at 2,17 times rated line to line voltage of the machine and not failed within 400 h;
– have a low dissipation factor that is stable with temperature up to the maximum operating temperature of the stator winding, verified by appropriate type testing.

6.5 PD measuring device

The electrical signals from the various types of sensors described in 6.4 can be measured and recorded using various measuring devices. The type of measuring device used may depend on the intended kind of further signal processing, analysis and interpretation. However, it is recommended to use a device which can, directly or by subsequent processing of the measured PD signals, provide at least a pulse magnitude distribution, a pulse phase distribution and a phase resolved partial discharge pattern according to Clause 10.

The PD measuring device typically consists of

– input amplifier and frequency filter;
– signal processing unit, e.g. pulse shaping, sample and hold, digitizer;
– noise suppression;
– visualization and phase synchronization.

In order to fully exploit the characteristics of the installed PD sensor, the frequency limits of the measuring device shall fit to the known frequency response of the installed sensor, to achieve a desired resulting frequency response of the complete measuring system in one of the frequency ranges according to 6.3.

6.6 PD measuring parameters

6.6.1 General

Various PD measuring parameters can be used for the visualization, analysis and interpretation of on-line measurements. In order to be able to assess the actual condition of the stator winding insulation, the used parameters should provide a sensitive means to characterize the nature of the PD from the machine under test as well as the development of PD processes over time when trending the machine condition by regular measurements.

6.6.2 PD magnitude

To evaluate the PD behaviour at least the PD magnitude q of each PD pulse should be measured and processed appropriately. The PD magnitude q of an individual pulse can be expressed in terms of voltage [mV] or in terms of apparent charge [nC], depending on the characteristic frequency range of the PD measuring system. A basic conversion of PD magnitudes measured in terms of voltage [mV] into charge [nC] and vice versa is usually not possible, especially in the higher frequency ranges.

The measured magnitude of the PD, and Qm in particular, may depend on the specifications of the recording instrument:

– In most digital PD instruments, when the pulse is detected, there is a "deadtime" during which the instrument will not respond to any new pulses appearing on the input. The deadtime is needed to digitize the pulse, determine its characteristics, and allow for any oscillations in the input pulse to decay to nearly zero. If a high magnitude pulse occurs during the deadtime, it will not be recorded. This effect may lead to some high magnitude pulses not being recorded, and Qm being in error.

– In most digital PD instruments there is a threshold below which pulses will not be recorded. This is normally to prevent triggering the instrument, with the associated deadtime, by low magnitude noise or disturbance that will inevitably be present. If the lower threshold is set too low, the PD instrument will be almost continuously triggered, and the associated deadtime will prevent the recording of legitimate PD data. In contrast, setting the lower threshold too high will mean that PD below the lower threshold will not be recorded.

– PD instruments that operate in the LF and HF frequency range may record a magnitude of the PD that is higher than actual. This is caused by the fact that two PD pulses may occur within a short enough time that the first PD pulse has not decayed to 0. This can lead to superposition of the two pulses, resulting in the magnitude of the second pulses adding to the magnitude of the first pulse. This is discussed in IEC 60270.

– In digital PD recorders the operating magnitude range is segmented into magnitude windows which determine the magnitude resolution of the instrument. For example, if the instrument can measure over the range 0 to 1 000 mV, and there are 100 magnitude windows, each magnitude window is 10 mV wide. The pulse counters in all digital instruments tend to measure the number of PD pulses per second, per magnitude window. If the scale is changed, and for example the PD is measured in the 0-2 000 mV range with 100 magnitudes, the magnitude window is 20 mV. The result is that when the magnitude scale is changed the number of pulses recorded may increase if the magnitude window width is increased. Thus scale changes may affect the determination of Qm, especially if Qm is a small fraction of full scale.

6.6.3 Additional PD parameters

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 the phase angle ϕ_i within the corresponding period of the line 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. This ensures that any additional derived PD parameters can be calculated afterwards on the basis of the originally measured data.

When using measuring systems working in the HF or VHF range, additional time domain parameters, like rise time, fall time or even the complete shape of each PD pulse can be measured, in order to subsequently apply special time and frequency domain analysis methods, e.g. for separating different PD sources.

7 Installation of PD on-line measuring systems

7.1 General

The components for on-line PD measuring can be installed in different extent. Depending from this extent of installation periodic or continuous on-line PD measurements can be performed (see 9.4 and 9.5).

7.2 Installation of PD sensors

Performing on-line PD measurements requires at least the installation of PD sensors in an appropriate location. This can be inside the machine housing, the neutral point cubicle or close to the bus duct. The PD sensor type determines sensor location and installation procedure.

For installation, commissioning, operation and maintenance of the PD sensors and its connection leads the supplier should provide adequate documentation. Installation and commissioning should be performed by skilled persons only.

If an additional component is connected between high voltage and ground (e.g. a high voltage capacitor) it should meet the insulation performance requirements at the place of installation, so that the insulation coordination of the system is not affected.

Furthermore the component should not introduce an unacceptable electrical fault risk to the system. On request, the supplier of the component should deliver information for a risk assessment, e.g. data from voltage endurance testing and failure statistics.

The PD sensors should withstand the normal operating conditions at its place of installation.

Metallic parts should be of non-magnetic material to avoid heating by the effects of the magnetic field.

For each machine phase at least one PD sensor is recommended, that should be positioned as close to the winding as possible. Optionally a PD sensor can be connected to the neutral point of the machine. At each phase a second PD sensor may be installed in some distance away from the terminals to gather directional information of pulses.

For the position, the mounting and the connection of the PD sensors the following considerations are important:

– The PD sensor and its connection leads shall not compromise the stator and phase bus insulation performance and the required clearances.
– The sensor mounting shall withstand all operating conditions like temperature, vibrations and short circuit transients, as loosening or deformation may initiate an electrical fault.
– PD sensors that are directly connected to high voltage potential should not be placed in an environment with excessive contamination and humidity. Surface contamination may cause leakage currents, eventually resulting in a surface tracking degradation or a pollution flashover.
– The PD sensor and its connection leads should not introduce partial discharge activity.
– The PD sensor and its connection leads shall not introduce induction loops.
– The connections to the high voltage potential and to ground potential should be as short as possible and of low inductance. Special attention is required to the mechanical quality of these connections as they may become loose due to vibrations.

7.3 Outside access point and cabling

As the PD sensor locations due to health and safety restrictions are normally not accessible during machine operation, an outside, unrestricted access point is recommended. The access point should allow the connection and disconnection of the PD measuring device to the PD sensor cables during machine operation without any risk for personnel and equipment. The access point should include over-voltage protection means in order to reduce the maximum voltage at its output to a safe level according to common technical rules and regulations, in case of a failure in the measurement circuit.

As the cable may introduce an entry point for electromagnetic noise by coupling processes, an appropriate degree of shielding and high quality connectors should be used. Due to continuous vibrations close to the machine all connections need to be of a mechanically robust type.

When the shield of a cable is grounded on both ends the shield establishes a ground loop, which may result in high currents, damaging the shield. There are different methods known to reduce such ground currents without compromising the shielding. The grounding design of the cable shall consider the grounding design of the PD sensor output and of the PD measuring device input.

Alternatively the PD information can be transferred via optical cable to the outside access point.

With an outside access point a portable PD measuring device can be safely connected at any time during machine operation and on-line PD signals can be acquired. Such a temporary connection of a PD measuring device is sufficient for snapshot measurements at specific intervals and requires only one measuring device for multiple machine units per site. This is usually called "periodic PD measurements" (see clause 9.4).

7.4 Installation of the PD measuring device

In order to perform a continuous PD measurement on a machine stator a PD measuring device needs to be permanently installed in addition to the PD sensors. To allow maintenance on or exchange of the device during machine operation, the installation of an access point according to 7.3 is recommended too. Regarding the cable connections the same considerations shall be taken into account as for the cables between the coupling units and the access point.

Furthermore a communication connection may be required between the PD measuring device and a computer that transfers control and status information as well as PD data. Depending on the distances, the site layout and the disturbance situation a connection method should be used, which operates reliable in the specific environment.

The PD data are continuously stored in the PD instrument or on the computer or any network drive if the computer is embedded in a distributed network.

Several PD measuring devices in a power plant, one for each machine, could be connected via a data network to a central computer station that allows the observation and analysis of PD activity in all machines from one place, for example the control room. However, other types of communication links may be possible.

7.5 Installation of operational data acquisition systems

In addition to the PD data, operational data from the machine should be automatically acquired and stored together with PD data. Operational data, such as active power, reactive power, winding temperatures, stator voltage and humidity of the cooling gas are of significance for the assessment of the stator winding system based on PD data interpretation. The operational data shall be linked to the PD data in the database or the PD data is transmitted to the plant computer.

Such machine operational data can be accessed by installing appropriate interfaces to the plant control system. Typical examples of possible interface installations are:

- The installation of a multi-channel analogue digital converter (ADC) module, which is capable to acquire process signals and transmits the digitized data via the communication network to the computer.
- The installation of a software interface on the computer, which interfaces the plant control system and provides the required operational data on the computer.

On-line PD measuring systems with permanently installed devices for PD acquisition and operational data acquisition systems are mandatory for performing "continuous on-line PD monitoring" (see 9.5).

8 Normalization of measurements

8.1 General

Due to pulse propagation, resonance and mutual cross-coupling in machine windings, mentioned in 6.2, calibration is not possible. Due to the wide variety of frequency ranges used by PD measuring systems, two normalization procedures are needed for different systems.

Although a calibration according to IEC 60270 does not apply for generators, for low frequency systems, experience shows that the amplitude of PD is often in the same range for similar generators and similar systems.

Alternatively, for high frequency systems, the difference between systems is so large that amplitude comparison between systems is no longer possible. Therefore, the procedure is aimed at quantifying the minimum detectable voltage drop at the generator terminals.

The choice between these two procedures is by agreement between the user and the provider. Both procedures can be performed on the same installation.

8.2 Normalization for low frequency systems

8.2.1 General

Normalization of the test circuit may facilitate comparisons between measurements on machines having similar design, taken with the same PD system. 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 normalization procedure can only be performed off-line.

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 does not provide an absolute benchmark for direct comparison of different machines. Nevertheless, normalization increases comparability of PD results between machines and therefore it will allow at least an order of magnitude comparison between different machines and different installations;
- for normalization of PD measuring systems in the low frequency range, reference pulse generators should be used that provide a constant pulse frequency spectrum in the frequency range of the measuring system;
- for a regular check of the function of the measuring system, e.g. major standstills can be used to repeat the normalization procedure.

8.2.2 Normalization procedure

Normalization of the test circuit is performed by injecting current pulses of a specified magnitude at the machine terminals or as close as possible to them, by means of a reference pulse generator. This is to simulate PD pulses as they appear at the machine terminals during the measurement.

Preferably the reference pulse generator shall operate somehow synchronous to the grid. This will help to identify the normalization pulses especially in noisy environment (see Figure 4).

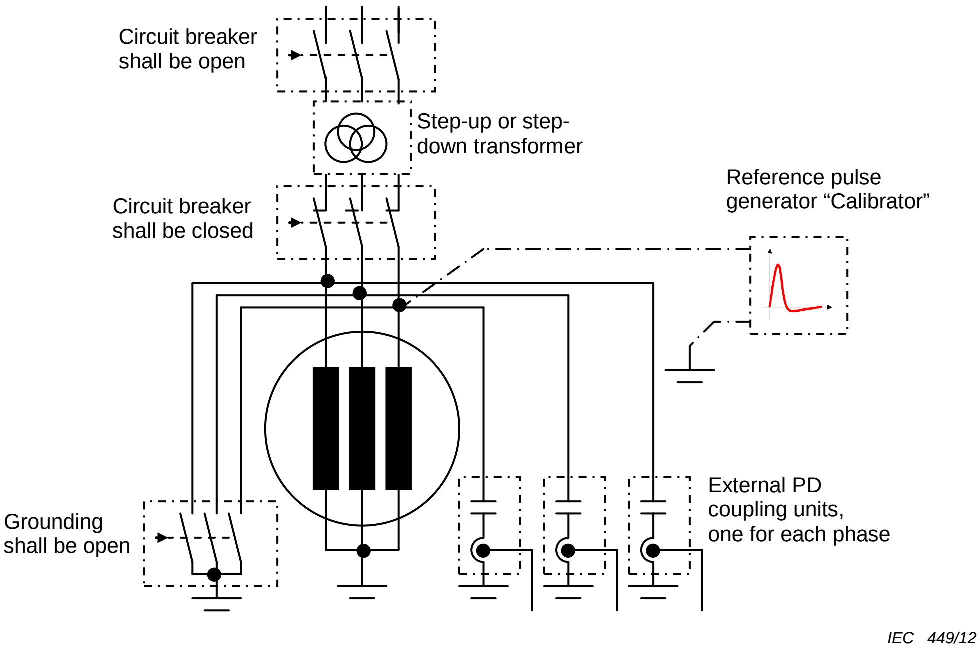


Figure 4 – Measuring object, during normalization

The procedure of normalization should be performed as follows:

a) All connections between machine and transformer, step-up or step-down, shall be closed.

b) Machine terminals shall not be grounded.

c) Neutral point connection shall be closed and connected to ground via direct link or grounding impedance (same as during operation).

d) If surge capacitors are installed on the machine these shall remain connected to the winding.

e) The reference pulse generator should be connected as close as possible to the terminals to consider the connection between terminals and PD sensors. In case of installed PD sensor at the neutral point, the normalization measurement will only be indicative due to the usually short distance to the ground.

f) Perform normalization measurement.

g) It is recommended to perform at least one measurement with disconnected pulse generator to verify the normalization and to verify the base noise that may superimpose the reference pulses.

h) To verify symmetry of all installed phases and PD sensors it is recommended to perform a normalization on all phases separately. Especially on large machines the lengths of the phase rings may differ significantly from phase to phase.

To verify the validity of the normalization, the ratio between the millivolts recorded by the PD instrument and the pulse generator charge shall be computed. Since the machine winding is symmetric, the mV/nC ratio is expected to be quite similar from one phase to the other. Since this procedure only applies to relatively low frequency systems, the phase rings influence should be limited.

8.3 Normalization / sensitivity check for high and very high frequency systems

8.3.1 Specification for the electronic pulse generation

The sensitivity check is performed by injecting voltage pulses on the conductor at the closest point to the insulation. This point is usually the terminal of the test object, and referenced as the terminal in the rest of this subclause.

The general setup for this sensitivity check is shown in Figure 5.

The pulse generator consists of a rectangular voltage pulse having a peak voltage of V_g and an internal resistance of R_g in series. The rise time t_R of this generator should be less than 1/f, where f is the upper frequency limit of the detection system. For example, if the upper cut-off frequency of the PD measuring system is 100 MHz, the electronic generator pulse rise time should be less than 10 ns.

The pulse duration shall be longer than the time response of the detection system. This time response is the time needed for the system to recover its initial condition after having being excited by an impulse. The fall time of the impulse has no importance.

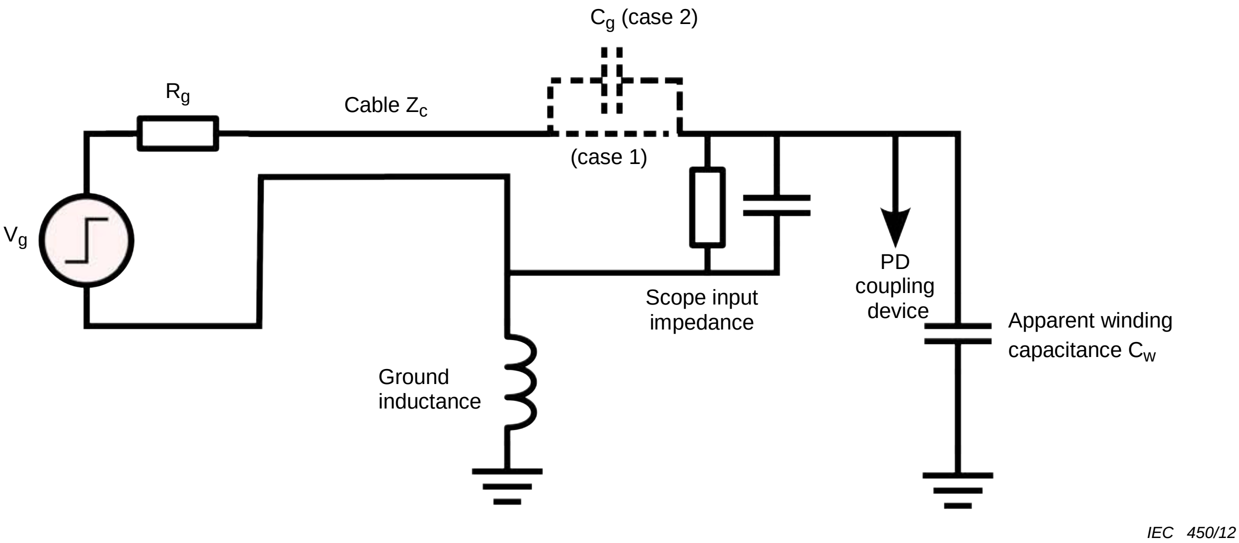


Figure 5 – Arrangement for sensitivity check

C_w represents the apparent capacitance of the winding. Note that this capacitance depends on the rate of the voltage change. Since high frequency attenuates more than low frequency, Cw will appear much smaller at the beginning of the impulse where the rise time is usually shorter.

There are two test conditions:

case 1) The time constant R_g C_w is less than t_R / 3 : the output of the pulse generator is directly connected to the terminal.

case 2) The time constant R_g C_w is more than t_R / 3 : a capacitor C_g shall be connected directly at the terminal in series with the pulse generator. This capacitor shall be chosen to obtain a resultant time constant of less than t_R / 3. The resultant time constant is $R_g \cdot \dfrac{C_g C_w}{C_g + C_w}$.

If the pulse generator is to be located far from the test object, a cable matching the impedance of R_g should be used ($Z_c = R_g$) to reduce the impulse distortion at the terminal. When the distance from the terminal up to the ground of the test object is more than 1/10 of the upper frequency limit wavelength of the detection system, the inductance connection to the ground is no more negligible (ground inductance in Figure 5). A low inductance ground plane should be installed to extend the ground of the generator for the pulse injection. The use of a wide copper foil is recommended. This ground point may be different from the coupling device ground point.

8.3.2 Configuration of the machine

For the sensitivity demonstration, the machine should be in the configuration indicated in Figure 4.

8.3.3 Sensitivity check

The sensitivity check procedure can only be performed off-line, unless a special high voltage injection capacitor C_g is used. But on-line pulse injection is a dangerous operation not covered in this document.

Using the setup of Figure 5, measure the minimum pulse voltage V_g at which the PD detector shows a detectable signal. This is, in mV, the sensitivity of the PD detection system.

The voltage pulse has to be measured directly at the terminal using a fast oscilloscope. If the electronic generator can be located very close to the terminal, at less than 1/10 of the upper frequency limit wavelength of the detection system, including the ground connection, the set pulse voltage Vg can be used directly.

If a supplemental capacitance C_g has to be used (case 2), the voltage level at the terminal may be too small for a valid measurement. This is the case when $C_g \ll C_w$.

The front of the voltage impulse is expected to oscillate. The voltage to consider for the sensitivity check is the peak value of the voltage recorded at the terminal. If very high frequency oscillations compared to the upper limit frequency of the detection system are measured, a filtering of this very high frequency component is to be performed.

In service, the background noise may increase significantly. As this check is performed off-line, it is recommended to record the PD output at various step voltage levels and injection electrode locations in order to estimate the minimum sensitivity level while operating. The minimum sensitivity level is the peak voltage of the step generator that is detectable above the noise floor limit. The real noise limit may be difficult to determine as the generator is normally producing PD while operating.

To verify symmetry of all installed phases and coupling devices, it is recommended to perform a sensitivity check on all phases separately. Especially on large machines, the lengths of the phase rings may differ significantly from phase to phase.

This technical specification does not recommend any minimum value. Also note that the sensitivity check is only valid for an impulse at the terminal, and due to attenuation, the sensitivity may drop rapidly for real PD located far from the terminal.

9 Measuring procedures

9.1 General

On-line PD measurements on rotating machines can be done on a periodic basis during normal operation of the machine, with a PD measuring device temporarily connected to the installed PD sensors via an appropriate access point, as described in Clause 7. As an alternative continuous on-line PD monitoring can also be performed, with a permanently installed PD measuring device and appropriate communication connections according to Clause 7. For both of these approaches it is recommended to perform an initial baseline measurement which can be used as a reference for future measurements and for trend analysis.

9.2 Machine operating parameters

One of the most important aspects of all on-line measuring procedures is the recording of machine operating conditions while PD data are being detected. The influence of machine operating conditions on the measurement results is often critical in subsequent data analysis and determination of PD sources. Therefore it is recommended to record especially the following operating parameters during each PD on-line test:

– stator current and voltage;
– active and reactive power ;
– winding temperature measured by slot RTD;
– cooling gas temperature and pressure;
– cooling water temperature for direct water cooled stator windings;
– humidity.

The operating parameters should be recorded simultaneously to the PD data and be stored with the same time scale on the same recording device to ensure the correct correlation of the data and thus a meaningful interpretation of the PD behaviour.

If other machines are running in parallel on the same high voltage bus, their influence with regard to external disturbances needs to be considered.

In order to identify the specific discharge sources, the factors that influence the discharge activity should be varied systematically by an appropriate measurement program. Since the measurement program may have an influence on the load regime of the operating unit, this program should be communicated in advance to the machine user.

9.3 Baseline measurement

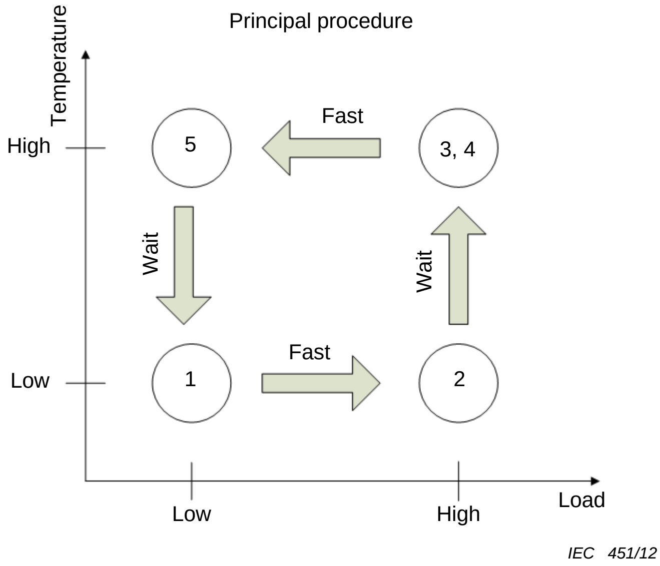
9.3.1 General

The initial PD on-line measurement performed on a machine gives an indication with regard to the condition of the insulation system at the time of the measurement. This is essentially a fingerprint of the PD activity within the insulation system, which is used as a basis for further trend analysis that will be established by future measurements. The initial fingerprint is best when the winding is new. However, it should be noted that the PD behaviour of a new winding usually stabilizes after the first 5 000 to 10 000 operating hours and thus the initial fingerprint of the new winding may show higher PD than subsequent measurements after some time of operation due to a conditioning effect.

9.3.2 Recommended test procedure

If a variation of load conditions is possible a series of PD readings should be taken under various load and temperature conditions. The following procedure according to Figure 6 can be viewed as a typical example for a baseline PD on-line testing. The load schedule provides data for a meaningful subsequent PD analysis, mainly considering load and temperature effects.

The load and temperature conditions should be varied according to the measurement sequence shown in Figure 6. Depending on the plant conditions the measuring sequence can be started with increasing load at point (1), or with decreasing load at point (3). Note that fast changes in load are not always possible in steam turbine generators.



Key

(1) Measurement at low load and thermally stable winding conditions

(2) Measurement at high load directly after relatively fast load increase

(3) Measurement at high load and thermally stable winding conditions

(4) Measurement at high load with significant change of reactive power and thermally stable winding conditions

(5) Measurement at low load directly after fast load decrease

Figure 6 – Recommended test procedure with consecutive load and temperature conditions

The measurements after load change (2) and (5) should be taken immediately. The stabilization of the temperature needs some time. Therefore, between each load point the stator winding temperature needs to be monitored such that the PD measurements (1), (3) and (4) are each performed when the temperature has stabilized. If change of active load is not possible, also a change in reactive load will at least provide a minimum stator current variation.

In order to get a sufficiently pronounced influence of the load conditions on the PD behaviour, the difference between low and high load should be at minimum 50 % of the nominal power.

If possible a measurement should also be carried out at nominal voltage and speed before synchronizing the machine to the grid. This allows a more reliable detection of defects, which depend on the electric field distribution only.

9.4 Periodic on-line PD measurements

Periodic on-line PD measurements are made at specific time intervals, which depend on the individual condition of the machine. If the measurements indicate a stable condition of the machine winding, then periodic measurements are typically made once or twice a year. In case of particular findings that may be related to insulation deficiencies, the time intervals can be shortened to minimize the risk that significant insulation deterioration may remain undetected between tests. It is further recommended to perform an on-line measurement before a maintenance standstill, to indicate possible weak points that need further consideration during maintenance work.

The full measurement program with load and temperature variation according to Figure 6 is recommended only in case there is a clearly noticeable PD activity that needs further detailed evaluation. At least a measurement at one load point and stable thermal conditions (high load (3), (4) according to Figure 6) should be performed on a regular basis. The load and temperature should not vary more than ± 10 % compared to previous measurements to ensure comparability and thus to ensure that a reliable trend analysis for subsequent measurements can be established.

9.5 Continuous on-line PD measurements

An alternative to periodic measurements is to install an acquisition system, which is capable of performing continuous PD measurements. The basic installation of a continuous PD monitoring module is the same as for the periodic system but, in addition, the PD measuring device and the controlling computer are installed on a permanent basis.

When PD data are continuously acquired the PD pattern and a set of calculated trending parameters according to Clause 10 can be derived directly from the originally measured data. A large amount of data is created, which cannot be stored indefinitely. Therefore, intelligent data reduction algorithms are needed, which automatically select the important trending parameters and patterns from the repetitive measurements for example per day and store them in a long-term database for later analysis purposes. Such automatic pattern selection can be carried out either simply time based with regular pre-defined time intervals, or more appropriately based on the development of the derived trending parameters, which are used for comparison with reference conditions of the insulation system.

The continuous PD monitoring system can be integrated into a supervisory diagnostic system that combines various diagnostic modules for the assessment of the machine condition. In that case it is essential to ensure appropriate communication links, which allow for connecting the system to a remote diagnostic centre, where a detailed analysis of the measured data can be performed.

The advantage of continuous on-line PD monitoring is that the PD data can be continuously trended in real-time and thus rapid changes of the PD behaviour can be detected and the risk of losing important information on the PD activity can be minimised. This allows a detailed PD analysis to be implemented on an event basis, rather than a traditional fixed time interval basis.

10 Visualization of measurements

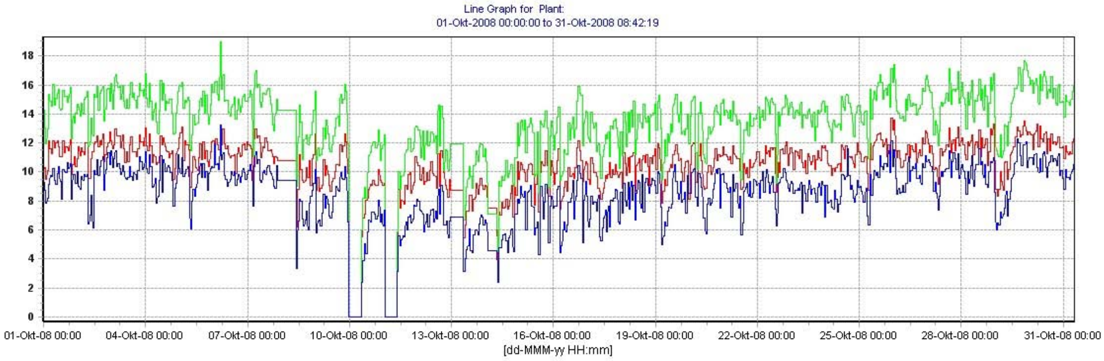
10.1 General

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 systems described in Clause 6 should be processed appropriately. Since the nature of damage to the insulation system, and therefore the risk of failure, is directly related to the particular type 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.

10.2 Visualization of trending parameters

As in an on-line situation the terminal voltage of the machine is a given parameter, it is not possible to determine the PD magnitude as a function of the terminal voltage. Useful, in the case of on-line measurements, is to visualize for example the PD magnitude or other characteristic quantities of specific PD phenomena as a trending parameter over a longer period of time (see example in Figure 7).

When using digital PD measuring devices the measured data can be analyzed later by appropriate methods and derived PD parameters can be calculated. 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. Statistical quantities like the NQN quantity (normalized quantity number) or others 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.).



IEC 452/12

Figure 7 – Example of visualization of trending parameters

When trending the PD magnitude or other PD parameters over time, it is important to simultaneously acquire information regarding temperature of the winding, ambient humidity, coolant temperature and pressure, excitation current, stator current, power factor and terminal voltage.

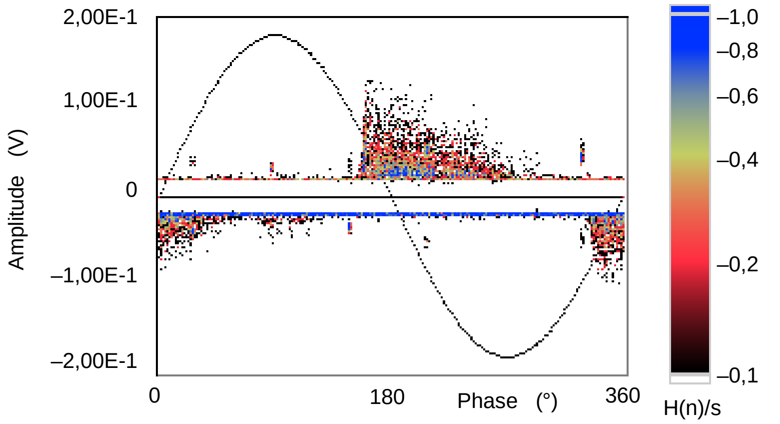
Besides basic time-related trending also the visualization of the relation of the PD magnitude with the other parameters can give information regarding development of specific failure mechanisms. It can be of use to introduce colours as a third dimension in the graphs to visualize the development in time.

10.3 Visualization of PD patterns

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.

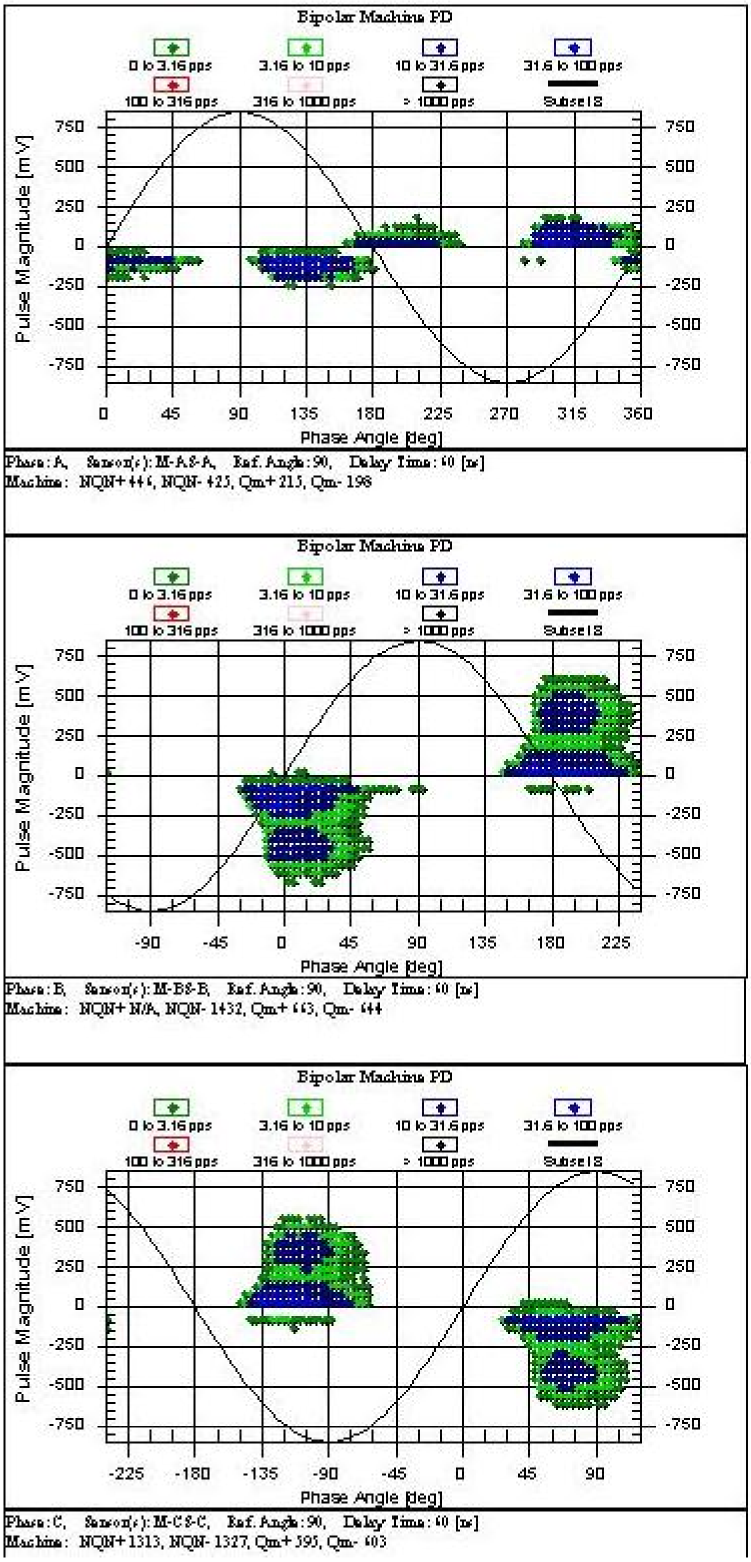
A PD pattern, which is recommended for identifying the causes of PD in stator winding insulation systems, is the Φ-q-n pattern in which the PD magnitude q is on the ordinate and the phase of occurrence Φ is on the abscissa for each individual PD pulse. Figure 8 shows an example of that pattern type. 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.

The Φ-q-n patterns obtained from on-line measurements can also be displayed as a three phase, phase shifted plot as shown in Figure 9, that can be efficiently used to identify phase to phase PD in the end-winding, and the effect of signal cross-coupling between different phases.



NOTE PD pulse magnitude q_i in [V]
Phase of discharge occurence Φ_i

Figure 8 – Example of a Φ-q-n partial discharge pattern, with colour code for the pulse number H(n)/s



IEC 454/12

Figure 9 – Example of a three phase, phase shifted Φ-q-n plot

11 Interpretation of on-line measurements

11.1 General

Interpretation is always comparative for stator windings. Since PD is often a symptom of a failure process and not a direct cause, it is not generally possible to specify a level of a PD quantity where there is a high risk of insulation failure. However, meaningful interpretation of on-line results is possible by using various sources of information, which may include not only the PD on-line results but also machine design knowledge, maintenance history, visual inspections, various off-line tests, operating conditions and appropriate expert knowledge.

In general, interpretation of on-line PD results should be performed in two steps. First it is fundamental for any maintenance planning to know if there are insulation problems, indicated by significant PD activity. If so, then the specific source of PD activity needs to be determined by a more detailed evaluation. 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 significant PD activity, i.e. on the type and possible location within the stator winding of the machine.

11.2 Evaluation of basic trend parameters

A powerful means of interpreting on-line PD data is to evaluate the trend of specific PD parameters over time. The parameters that can be used for that trend evaluation are described in 10.2. For new machines it is essential for reliable trend evaluation to get an initial fingerprint of the PD activity by performing a baseline measurement according to 9.3. This initial fingerprint can then be used for comparison with subsequent regular or continuous PD measurements.

If for example the PD pulse magnitude, Q_m, is used as the trending parameter, meaningful interpretation can occur by

– trending Q_m on the same machine over time, using the same PD measuring system;

– comparing the Q_m trend from different phases of one machine, using the same PD measuring system;

– comparing the Q_m trend from several machines with the same design, using the same PD measuring system.

However, other trend parameters according to Clause 10, which provide significant information on the development of winding deterioration, may be used for trend analysis. In general it is meaningful to use not only one but various PD parameters for simultaneous trending, which provide additional information on the characteristic PD behaviour. If the winding condition is stable over time without significant deterioration, then the observed trend parameters will behave stable as well. However, if the winding deteriorates due to operation in service, then for example Q_m will usually increase over time. Doubling of Q_m over one year may be an indication that significant deterioration has occurred. Additional off-line 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;

– in the case that the baseline measurement on a new winding shows relatively high PD compared to other similar machines, the user of the machine may seek from manufacturers assurance that the new winding was made with the normal quality level that the manufacturer has achieved in the past and that the initial fingerprint shows a PD behaviour, which is normal for that kind of machine and a new stator winding;

– the PD behaviour may be affected by machine operating conditions, e.g. winding and core temperature, load, cooling gas temperature or ambient conditions. Variations in PD as a result of operating conditions shall be understood and distinguished from those caused by progressive ageing of the insulation system, to establish accurate assessment of the PD trend;

- variations of Q_m of a certain percentage, for example ± 25 %, may be normal, due to more or less statistical behaviour of PD processes;
- for determining the specific type of PD process it is not sufficient only to detect and trend individual PD parameter values, but it is necessary also to assess the phase resolved PD pattern according to 11.3;
- a reliable assessment of the PD behaviour requires that each detected PD phenomenon is trended individually, which is only possible by analysing the phase resolved PD pattern according to 11.3;
- in older machines with high PD activity it is not uncommon for the PD trend to stabilize even though the deterioration is progressing;
- when trending the PD behaviour over time the PD magnitudes may also decrease even though significant deterioration of the insulation is present. Decreasing trends are thus not indicative of any insulation recovery.

When performing only trending of parameters over time and the trend is high, or the individual reading is high, then the PD data should be further analysed to determine the probable cause for the high PD activity. In this case, the analysis of phase resolved PD patterns (Figures 8 and 9) in accordance with 11.3 is useful for identifying the PD sources.

11.3 Evaluation of PD patterns

11.3.1 General

In order to assess the stator winding condition the, ϕ-q-n–pattern (Figure 8), recorded during periodic measurements or during continuous monitoring, should be used to determine the specific type of any PD activity within the stator winding of the machine.

When using the ϕ-q-n–patterns, it may be possible to separate various PD sources from each other and to trend their PD behaviour separately. When knowing the specific type and location of any PD activity within the winding it is also possible to assess the risk associated with individual PD sources. Since each PD process may have its own critical level of PD magnitude it is not recommended to use PD magnitude alone as an indicator of risk of premature failure.

11.3.2 PD pattern interpretation

The aim of PD pattern interpretation is to identify the dominating PD source and to separate PD resulting from various PD sources within the stator winding. With this information, it is possible to

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

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

- trending the PD pattern on the same machine over time, using the same PD measuring system;
- comparing the PD patterns from different phases of one machine, detected at the same time, using the same PD measuring system;
- comparing PD patterns from several machines with the same design, using the same PD measuring system.

To facilitate comparison between measurements 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. With some restrictions such a database can also be utilized for the direct comparison of PD measurements with those of machines of similar design and insulation system, which provides further useful information.

The specific relationship between the source of the PD, its typical behaviour and also its implications for the risk of stator winding insulation failure, is usually based on past experience verified in practice.

Annex A shows some examples of the principle appearance of phase resolved PD patterns and gives some general interpretation rules that can often be applied for stator winding PD.

11.4 Effect of machine operating factors

11.4.1 General

Further information on the likely deterioration mechanism can be obtained by analyzing the effect of various machine operating factors. Particularly the influence of load and temperature on the specific PD behaviour can be efficiently used to identify typical deterioration mechanisms resulting in stator winding PD.

11.4.2 Machine operating factors

The main machine operating factors that influence the PD behaviour are:

a) Load conditions:

   The load conditions of the machine given as active and reactive load are characterized by the actual stator current, the stator voltage and the power factor. These parameters directly determine the winding and core temperature of the machine as well as the electrical and mechanical stresses on the stator winding insulation system.

b) Machine operation mode:

   The operation mode of a machine that may be operated in peak or base load, may have an influence on the ageing behaviour of the stator winding insulation system due to thermal and mechanical stresses.

c) Cooling system:

   Depending on the rated machine power different cooling systems are used. The stator winding may be direct or indirect air- or hydrogen-cooled or even direct water-cooled. The different cooling methods and type dependent designs significantly influence the thermo-mechanical stress of the stator winding components. In addition, for gas cooled machines, the cooling gas pressure influences the PD activity.

d) Ambient conditions:

   The main ambient influence factors on the PD behaviour of the machine are humidity and particularly contamination, like partly conductive grease, dust, oil, etc., which may for example occur in open-circuit air-cooled machines.

Due to these influencing factors, for the analysis of the PD behaviour in correlation to the machine operating conditions, it is recommended to record the operating parameters according to 9.2.

11.4.3 Steady state load conditions

When performing periodic on-line measurements load conditions for each measurement need to be the same in order to be able to compare subsequent measurements and to reliably assess the trend behaviour. In addition it is necessary to determine if the noise conditions for the measurement have changed.

To ensure comparable machine conditions, the operating factors mentioned in 11.4.2 need to be recorded. If the machine conditions are the same for subsequent measurements and the trend parameters or the phase resolved PD patterns show significant deviations between measurements, then this may indicate changes of the winding insulation condition. In that case possibly changed noise conditions need to be identified and the type of PD source should be determined according to the characteristic shape of the PD patterns.

To further verify the type and/or location of PD sources a systematic variation of the operating machine parameters, as described in the next clause, is very helpful.

11.4.4 Transient load conditions

Variations of the PD trend parameters and/or the PD patterns with respect to operating parameters can assist in identifying the source of PD and its relative severity. Some new windings may require several months of operation before stable "benchmark" readings are possible because of the continued cure of resin and slot contact effects.

a) *Change with load*: When temperature and voltage are held constant, a change of the PD magnitudes within the negative voltage half-wave between low load and high load is indicative of a loose winding. This effect is due to stronger electromagnetic forces acting on the winding at higher load. Such signs merit early investigation because erosion of thermosetting groundwall insulation caused by the combination of slot discharge and electromechanically induced vibration can be rapid.

b) *Change with power factor*: When temperature and voltage are held constant, a change of the power factor allows to distinguish between PD caused by high electric fields and arcing effects due to electromagnetic current forces. This can be identified with the ϕ-q-n pattern since in contrast to PD resulting from high electric fields, arcing effects driven by electromagnetic forces lead to typical phase shifts of PD pulses within the discharge pattern.

c) *Change with temperature*: When load and voltage are held constant, a change of the PD magnitudes as the temperature increases or decreases, is usually indicative of discharges mainly resulting from the slot portion of the winding. This may be a sign of delaminations between inner conductor and insulation or between layers of the main insulation or even a sign of slot discharges. The influence of temperature changes on the behaviour of PD from the end-winding region cannot be assessed.

d) *Change with gas pressure*: In the case of hydrogen-cooled machines, there may be an opportunity to make PD measurements at different gas pressures. These results can be useful in confirming the sources of PD. If there is an increase in PD with decreasing pressure, the PD is occurring within the generator enclosure and not external to the generator. Especially surfaces discharges will be more prominent at low gas pressure. When decreasing the gas pressure, caution is needed in particular for aged stator winding insulations, since the loss of external gas pressure may lead to mechanical overstressing of the insulation due to the still existing internal gas pressure in voids and delaminations.

e) *Change with humidity*: The humidity of the surrounding cooling gas will have an effect on the behaviour of surface discharges. Lower PD has been attributed to the surfaces of the end arms at times when the humidity is high because of a homogeneous field grading effect on the winding surface. However, in the presence of severe contamination higher humidity may result in local conductive paths that lead to additional surface discharges. PD within the ground insulation does not change with humidity.

12 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.

ON-LINE PARTIAL DISCHARGE TEST REPORT

PARTIAL DISCHARGE TEST DATA

Date:

Customer:

Plant:

Unit:

Safety responsible:

Operator(s)

Name	Function

(add more lines if needed)

<table>
<tr><td>Detector

Manufacturer:
Type:
Serial:
Bandwidth:
Output unit (mV/pC):</td><td>PD Sensor

Manufacturer:
Year manufactured:
Type:
Capacitive
Inductive
Stator slot coupler

Capacitance (if applicable):
Distance between sensor and connection point:</td></tr>
<tr><td colspan="2">Sensitivity check:
Indicate if any off-line test has been performed earlier to check the sensitivity of or calibrate the measurement chain.
Make reference to any previous report if available.</td></tr>
</table>

Operating point(s) during PD tests

Ambient temperature:

Ambient relative humidity:

Voltage (kV)	**Active power** (MW)	**Reactive power** (MVA)	**Average temperature** (°C)	**Cooling medium pressure** (psi)	**Time**

(add more lines if needed)

MACHINE DATA

The following data were provided on (date) ____________ by Mr/Ms:

Nameplata data

Manufacturer:

Type and serial number:

Year manufactured:

Rated Voltage (kV)

Rated power (MVA)

Rated power factor:

Frequency (Hz):

Speed (RPM):

Number of internal ways:

Stator cooling system:

Indirect: air/hydrogen/carbon dioxide

Direct: air/hydrogen/water

Rated pressure of cooling medium (if applicable):

Insulation system data

Insulation class:

Manufacturer (if rewound):

Manufacturing technology (resin rich/VPI):

Grading system type (paint/tapes):

Year last rewinding (if applicable):

Year last rewedging (if applicable):

External environment

Step-up transformer voltages:

Distance between machine and transformer:

Operational data

Power plant type (Coal/Oil/Gas/Hydro/Nuclear):

Operation mode (continuous/intermittent):

Standby mode (hot/cold, applicable only to intermittent units):

The following data should be reported starting from manufacturing or last rewinding (if any) to date:

Number of starts:

Number of hours (or equivalent operating hours):

Average load:

Peak load:

Average winding temperature:

Maximum winding temperature:

Number of differential relay trips in phase U _____ V _____ W _____

Number of maximum current relay trips in phase U _____ V _____ W _____

Other notes

Annex A
(informative)

Examples of Phase Resolved Partial Discharge (PRPD) pattern

A.1 Principal appearance of phase resolved PD patterns

The following figures show some examples of phase resolved PD patterns in a stylized form, which can typically be found for defects in stator winding insulation systems. It should be noted that different patterns than shown here may also occur for different PD sources. Users should be aware that various additional effects, not shown here, can occur during PD on-line measurements that may also produce other characteristic PD patterns. Especially strong superposition of patterns is possible in practical cases and also variations in pattern shape, PD frequency or other characteristics.

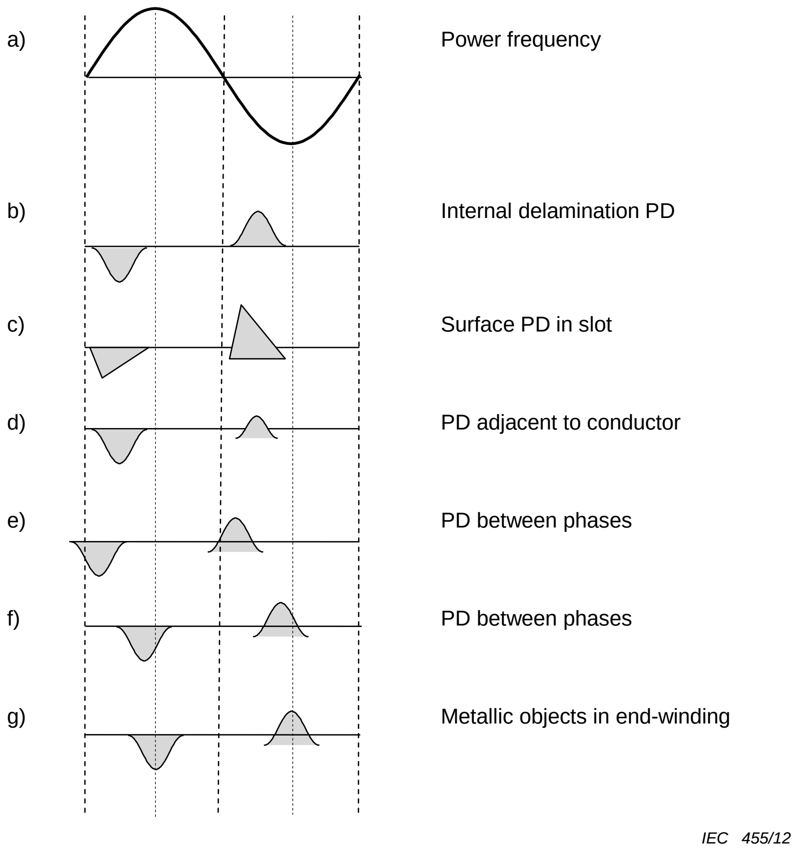


Figure A.1 – Stylized examples of PD phase resolved patterns

Even if the specific patterns detected during on-line measurements may deviate from the patterns shown in Figure A.1 above, it is possible to make the following general remarks:

– When the PD pulses, which mainly occur during the negative half-cycle of the voltage waveform, predominate in magnitude (example c in Figure A.1), the source of the PD likely involves a damaged conductive slot coating due to loose vibrating stator bars or coils. This process is usually more pronounced during on-line measurements at higher load.

– When the PD pulses, which mainly occur during the positive half-cycle of the voltage waveform, predominate in magnitude, the source of the PD can be expected to be at or near the copper strands and may indicate an incomplete bond between the insulation and the copper conductor (example d in Figure A.1). In the case of multiturn coils there may be an inadequate bond between the turn insulation and the groundwall insulation.

– When the PD pulses in the positive and negative half-cycle are in the same range of magnitude (examples b, e, f, g in Figure A.1), the source of PD can be expected to be surface discharges at the end-winding or internal discharges due to voids or delamination of the main insulation.
– Note that examples e and f in Figure A,1 should be taken together as a pair. If the PD is occurring between two phases, the PD detected in one phase will tend to be shifted right (closer the zero crossing of the AC cycle), whereas the same PD detected in the other phase will be shifted left (closer to the peaks of the AC cycle).
– During on-line measurements cross-coupling effects between different phases may occur, which can significantly influence the PD patterns. Such effects usually complicate the identification of individual PD sources.

A.2 Example of typical PRPD patterns recorded on laboratory

A.2.1 General

The following measurements were taken under well controlled laboratory conditions, so that the PD processes are well known while the noise level is kept very low. For every type of defect simulated in laboratory, the phase resolved φ-*q*-*n* patterns were recorded many times over a long period of time, in order to validate the repeatability of the PRPD patterns.

A.2.2 Internal discharges

A.2.2.1 Internal voids

Internal PDs are generated in an air or gas-filled pockets embedded in the main insulation. They result from the manufacturing process and do not indicate ageing factors. Under normal circumstances, internal discharges do not lead to marked ageing.

Figure A.2 illustrates a PRPD pattern recorded in laboratory, when only internal PD activity was present on the bar. The main characteristic of the resulting PRPD pattern is the symmetry between the positive and negative PDs, combined with a rounded shape. Typically, negative PDs occur between 0° and 90° and positive PDs occur between 180° and 270°.

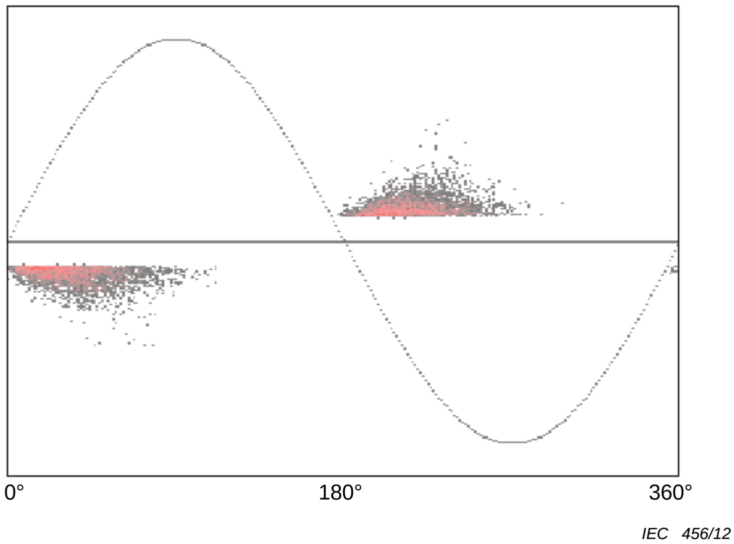


Figure A.2 – Example of internal void discharges PRPD pattern, recorded during laboratory simulation

A.2.2.2 Internal delamination

Internal delamination PDs are generated in an air or gas-filled longitudinally elongated pocket embedded in the main insulation. They often result from overheating or from extreme mechanical forces which both lead to separation of large areas between insulation layers.

A typical PRPD pattern resulting from internal delamination is illustrated in Figure A.3. Like internal discharges, the PRPD pattern will be symmetric in amplitude and PD count, again reflecting the symmetry of the defect. Even if this type of defect is similar to internal void discharges, the PD count will be much higher, mostly because of larger PD sites. Also, the resulting PRPD pattern will show a less rounded shape than internal void PRPD pattern, sometimes almost triangular shape. Older insulation systems are more subjected to internal delamination than mica-epoxy insulation.

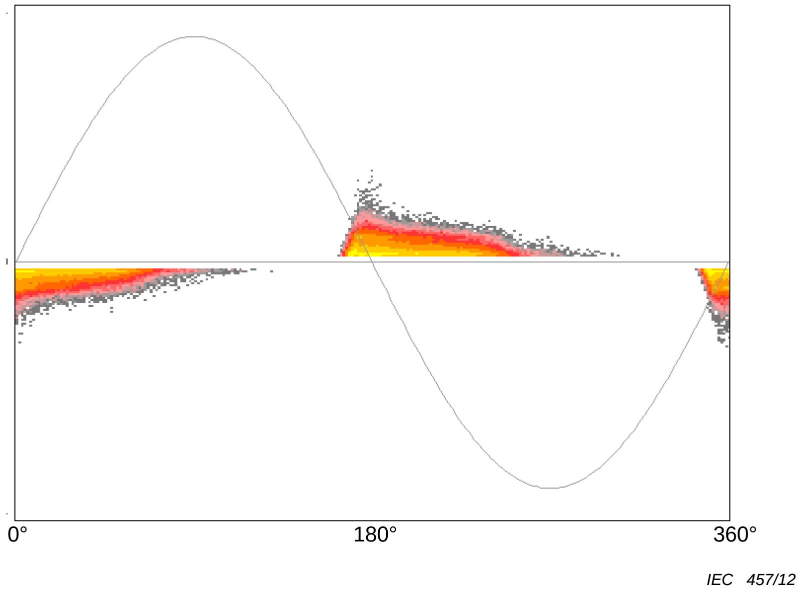


Figure A.3 – Example of internal delamination PRPD pattern, recorded during laboratory simulation

A.2.2.3 Delamination between conductor and insulation

Delamination PDs between conductors and the main insulation are generated in an air or gas-filled longitudinally elongated pockets embedded between the main insulation and the high-voltage copper conductor. They often result from overheating or from extreme mechanical forces which both lead to separation of large areas between the layers.

A typical PRPD pattern resulting from delamination between conductor and insulation is shown in Figure A.4. Since this type of defect is asymmetric (copper on one side and insulation on the other side), the corresponding PRPD pattern will also be asymmetric. Negative PDs, occurring during the positive voltage half-cycle, will be higher in number and amplitude than positive PDs occurring during the negative voltage half-cycle.

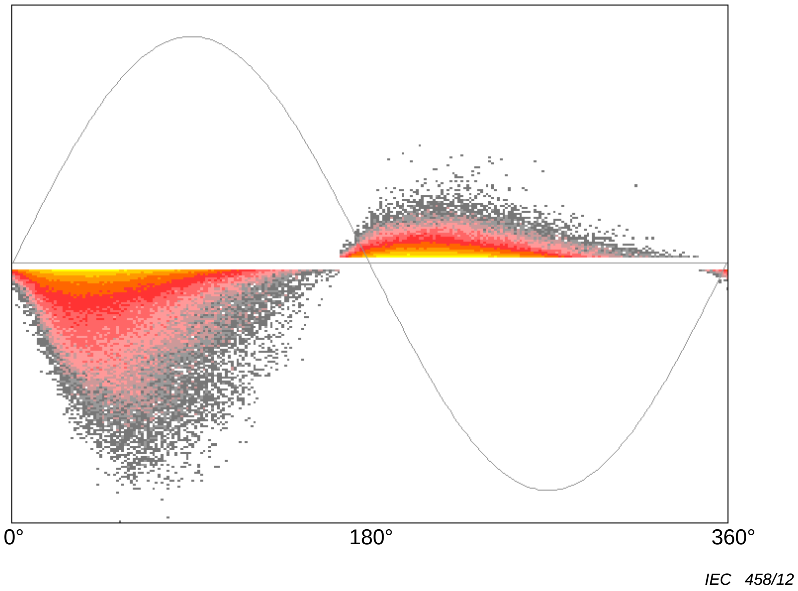


Figure A.4 – Example of delamination between conductor and insulation PRPD pattern, recorded during laboratory simulation

A.2.3 Slot partial discharges

Slot PDs are generated in an air or gas-filled pocket, inside the stator core, between the surface of a bar and the stator core. This activity will occur when the electrical contact between the S/C coating of the bar and the slot is lost or is too high.

This type of activity, simulated in laboratory, is illustrated in Figure A.5, left. A typical PRPD pattern corresponding to this type of activity is shown in Figure A.5, right. Since a slot PD defect represents an asymmetric defect (bar insulation on one side, stator core on the other), the PRPD pattern will also be asymmetric. The slot PRPD pattern is characterized by an asymmetry in favor of positive discharges, occurring during the negative voltage half-cycle, combined with a triangular shape and a sharp slope at the onset of the positive PD pattern.

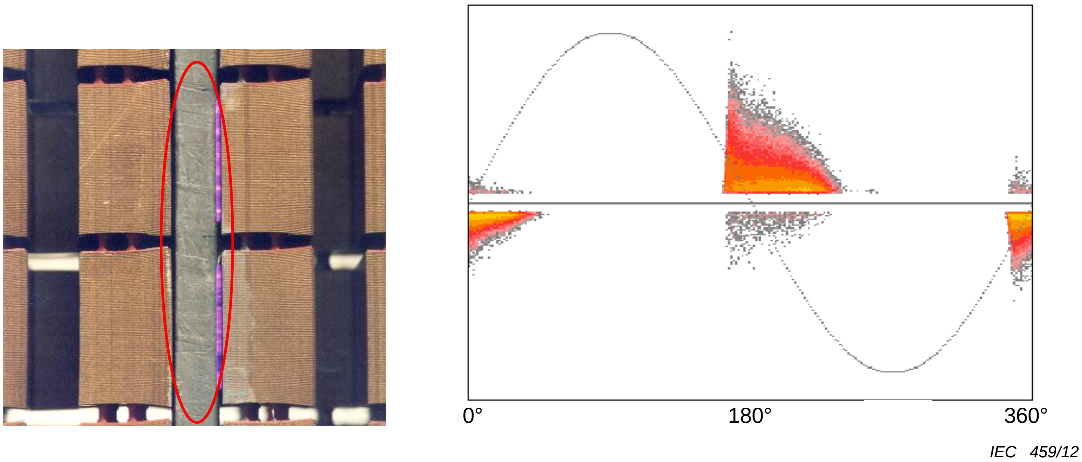


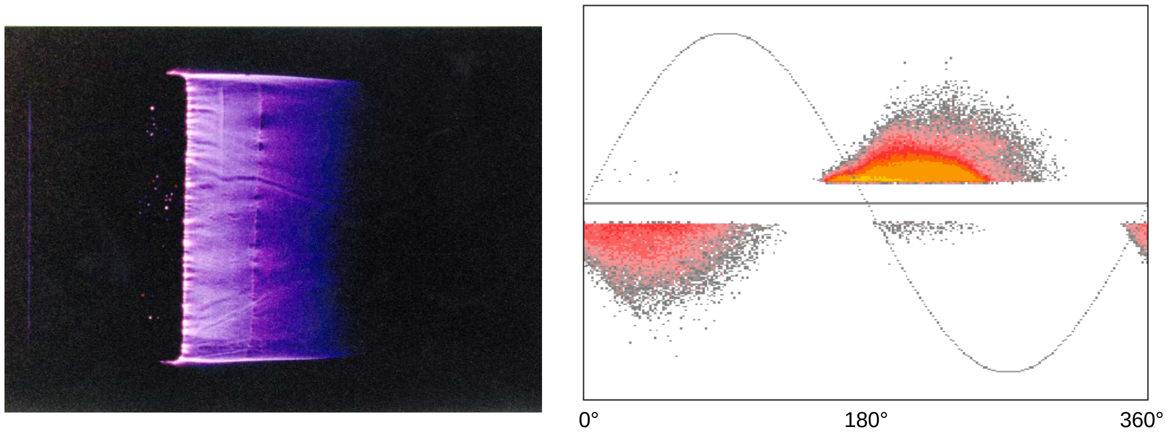
Figure A.5 – Slot partial discharges activity and corresponding PRPD pattern, recorded during laboratory simulation

A.2.4 Discharges in the end-winding

A.2.4.1 Corona activity at the S/C and stress grading coating

This activity will occur directly at the junction of the S/C and the stress grading coating when the field grading system is not adequate, resulting in a high local electrical stress.

This type of activity, simulated in laboratory, is illustrated in Figure A.6, left. In this figure, the S/C coating is on the left side, while the grading coating is on the right. A typical PRPD pattern corresponding to this type of activity is shown in Figure A.6, right. It is characterized by an asymmetry in favor of positive discharges, occurring during the negative voltage half-cycle, combined with a rounded shape. In some cases, the asymmetry in maximal amplitude may tend to disappear, but the asymmetry in the number of PDs will still be present.

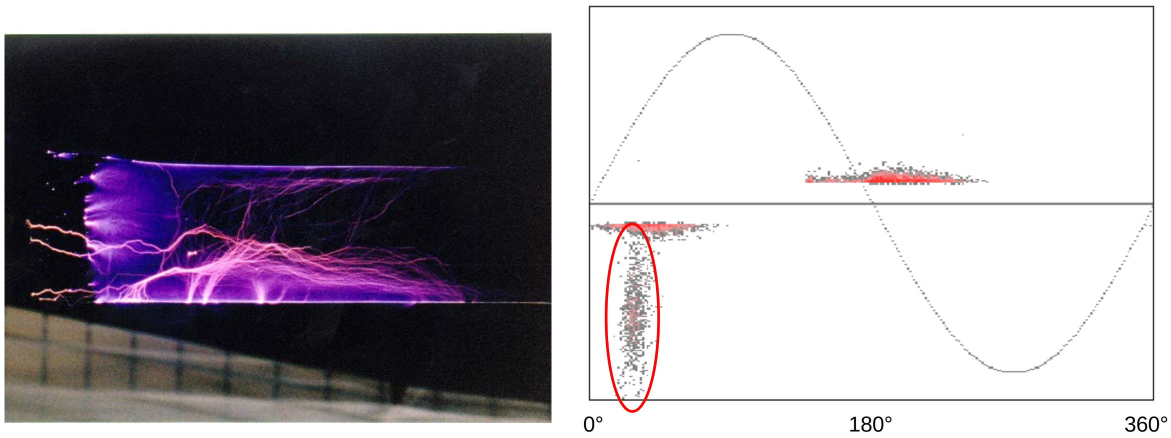


IEC 460/12

Figure A.6 – Corona activity at the S/C and stress grading coating, and corresponding PRPD pattern, recorded during laboratory simulation

A.2.4.2 Surface discharges tracking

This type of activity will occur along the winding overhang due to contamination at the air/insulation interface. This activity, simulated in laboratory, is illustrated in Figure A.7, left. In this figure, the S/C coating is on the left side, while the grading coating is on the right. A typical PRPD pattern corresponding to this type of activity is shown in Figure A.7, right. Surface tracking PDs are encircled in the red ellipse. The main characteristic of surface tracking is a vertical cloud of PDs, combined with a low PD count. In some cases, PDs can occur in both polarities.



IEC 461/12

Figure A.7 – Surface tracking activity along the end arm and corresponding PRPD pattern, recorded during laboratory simulation

A.2.4.3 Gap type discharges

This type of activity will occur between two bars in the winding overhang, or between a bar and the press finger of the stator core. The two activities, simulated in laboratory, are illustrated in Figure A.8, left. The top one represents a PD activity between two bars, while the lower one illustrates a PD activity between a bar and the press finger of the stator core. Typical PRPD patterns corresponding to these activities are shown on the right. The main characteristic of a gap type discharge activity is a horizontal cloud of PDs of relatively constant amplitude, present in both polarities of the voltage. Since both defects are very similar, the PRPD patterns will also look similar, so that it is almost impossible, based only on PRPD patterns, to differentiate between the two phenomena.

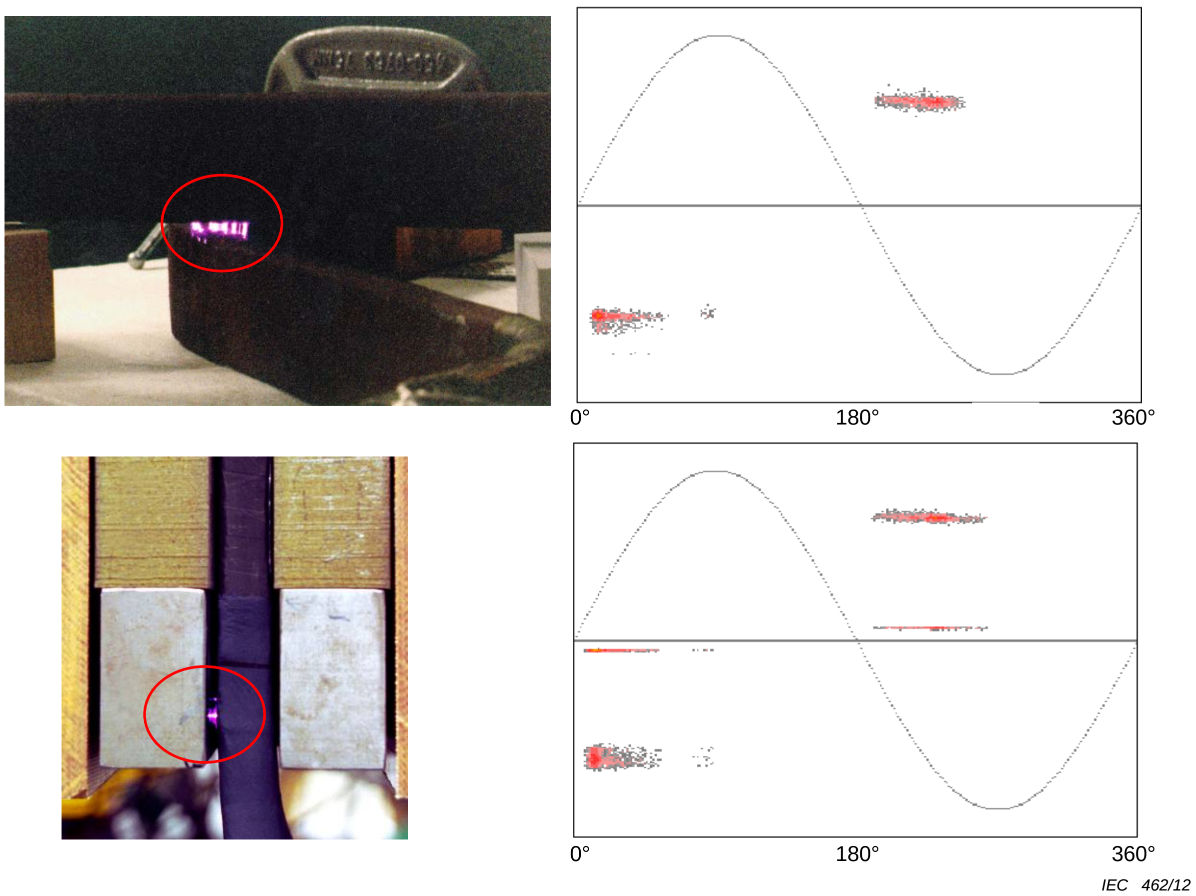


Figure A.8 – Gap type discharge activities and corresponding PRPD patterns, recorded during laboratory simulations

A.3 Example of typical PRPD patterns recorded on-line

A.3.1 General

The following measurements were taken on-line, under stable temperature conditions. All the PRPD patterns shown here were recorded in a higher frequency range (2 MHz – 20 MHz), in an attempt to eliminate noise. In some cases, visual inspections were performed after the PD measurements. Illustrations of the degradation of the insulation are given.

A.3.2 Internal discharges

A.3.2.1 Internal voids

Internal PDs are generated in an air or gas-filled pockets embedded in the main insulation. They result from the manufacturing process and do not indicate ageing factors. Under normal circumstances, internal discharges do not lead to marked ageing.

Figure A.9 illustrates a PRPD pattern recorded on-line, showing an internal void discharges activity. The main characteristic of the resulting PRPD pattern is the symmetry between the positive and negative PDs, combined with a rounded shape.

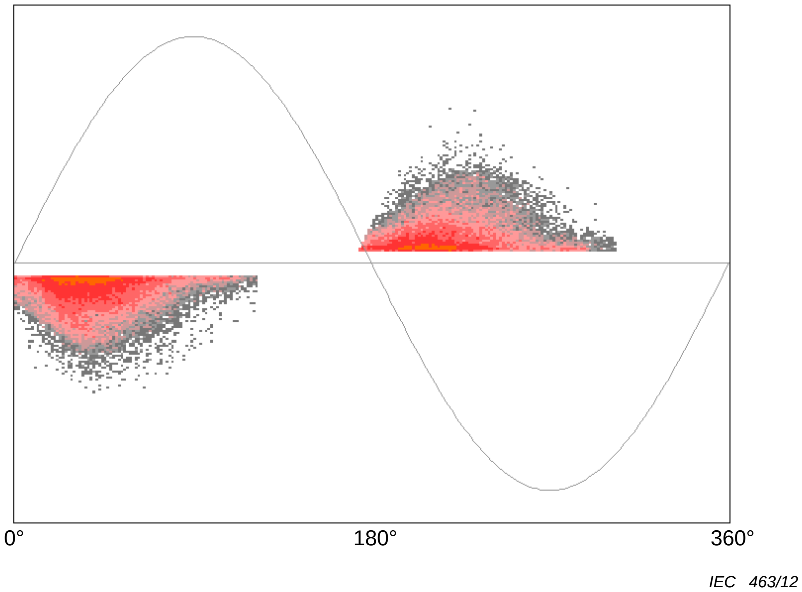


Figure A.9 – Example of internal void discharges PRPD pattern, recorded on-line

A.3.2.2 Internal delamination

Internal delamination PDs are generated in an air or gas-filled longitudinally elongated pocket embedded within the main insulation. They often result from overheating or from extreme mechanical forces which both lead to the separation of large areas between insulation layers.

Figure A.10 illustrates a typical PRPD pattern recorded on-line, showing an internal delamination partial discharge activity. The main characteristic of the resulting PRPD pattern is the symmetry between the positive and negative PDs, combined with a triangular shape.

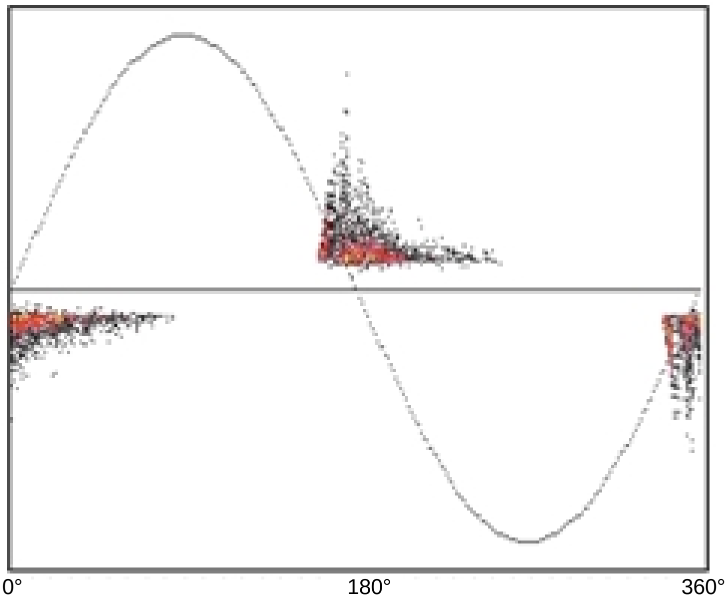


Figure A.10 – Example of internal delamination PRPD pattern, recorded on-line

A.3.2.3 Delamination between conductor and insulation

Delamination PDs between conductors and the main insulation are generated in an air or gas-filled longitudinally elongated pockets embedded between the main insulation and the high voltage copper conductor. They often result from overheating or from extreme mechanical forces which both lead to the separation of large areas between these layers.

A typical PRPD pattern, recorded on-line, resulting from delamination between the conductor and the insulation is illustrated in Figure A.11. Since this type of defect is asymmetric, the corresponding PRPD pattern will also be asymmetric. Negative PDs, occurring during positive voltage half-cycle will be higher in number and amplitude, than positive PDs occurring during the negative voltage half-cycle.

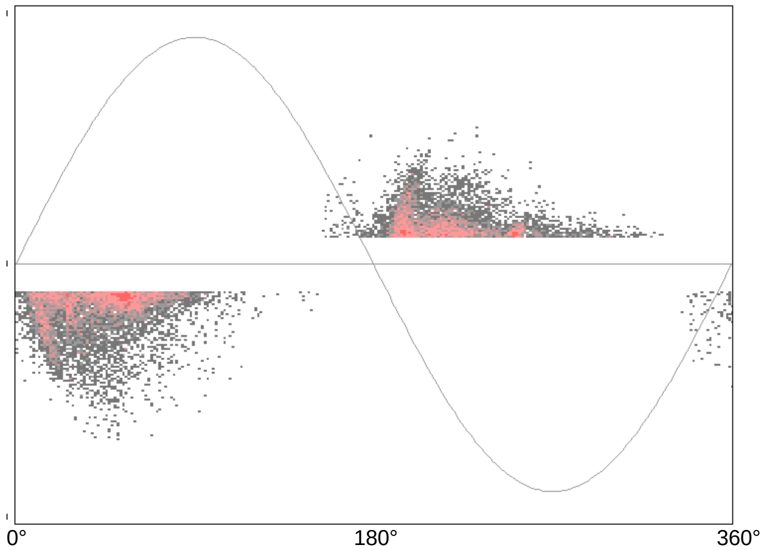


Figure A.11 – Example of delamination between conductor and insulation PRPD pattern, recorded on-line

A.3.3 Slot partial discharges

Slot PDs are generated in an air or gas-filled pocket, inside the stator core, between the surface of a bar and the stator core. This activity will occur when the electrical contact between the S/C coating of the bar and the slot is lost or is too high.

Figure A.12, left, illustrates the degradation resulting from slot PD activity. The S/C coating was completely eroded in some spots. Rust deposit can also be noticed on the surface of the bar. Similar deposits are normally also observed on the surface of the stator core, facing the defects observed on the bar. Figure A.12, right, illustrates a PRPD pattern of slot PD activity recorded on-line. It is characterized by an asymmetry in favor of positive discharges, occurring during the negative voltage half-cycle, combined with a triangular shape.

NOTE In the presence of large amounts of rust deposit on both sides of the defect, resulting from long time exposure to slot PD, the asymmetry in the PRPD pattern may be less pronounced, because the insulated surface will become more conductive, while the conductive surface will become more resistive.

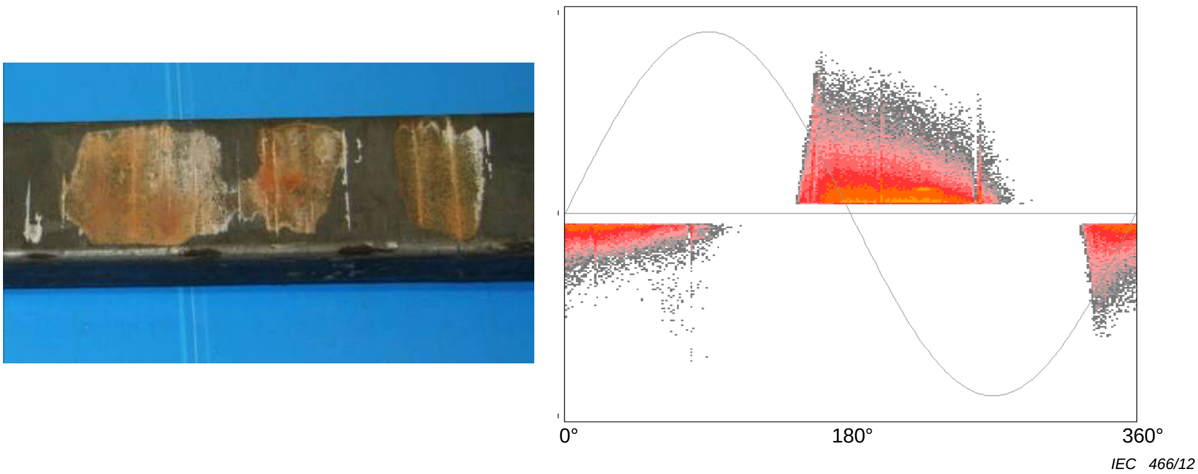


Figure A.12 – Degradation caused by slot partial discharges activity and corresponding PRPD pattern recorded on-line

A.3.4 Discharges in the end-winding

A.3.4.1 Corona activity at the junction of the slot coating and stress control coating

This activity will occur directly at the junction of the slot coating and the stress grading coating, when the field grading system is not adequate, resulting in a high local electrical stress.

Figure A.13, left, illustrates the degradation resulting from the long term attack by corona activity at the S/C and stress grading coating. A PRPD pattern recorded on-line is shown on the right of the picture. We can observe the main characteristic of corona activity at the junction, namely an asymmetry in favor of positive discharges, occurring during the negative voltage half-cycle, combined with a rounded shape.

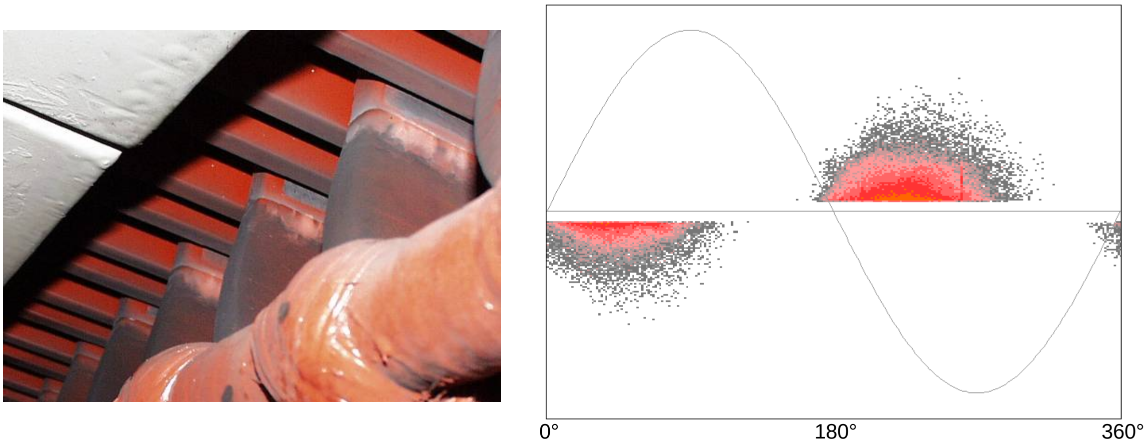


Figure A.13 – Degradation caused by corona activity at the S/C and stress grading coating and corresponding PRPD pattern, recorded on-line

A.3.4.2 Surface tracking discharges

This activity will occur along the winding overhang due to contamination at the air/insulation interface. This type of activity can be very sporadic, and highly depends on temperature and humidity conditions. In the PRPD illustrated in Figure A.14, surface tracking PDs are encircled in the red ellipse. Other PDs are of internal nature and cross-coupling between phases.

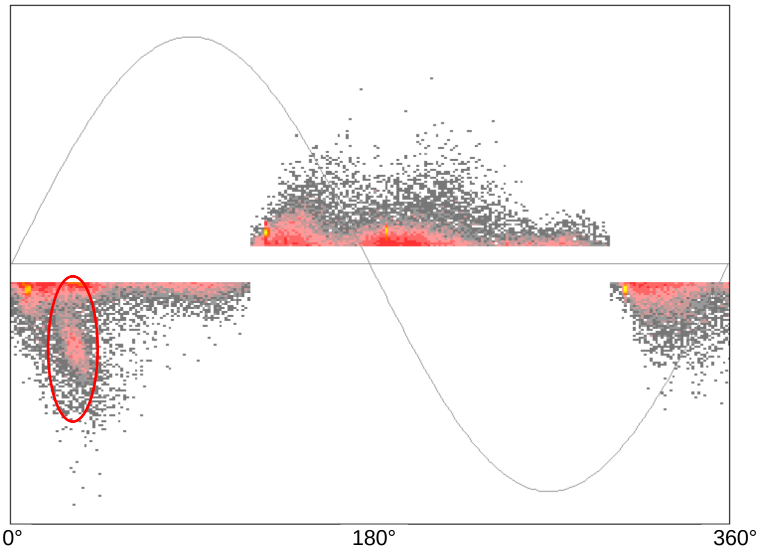


Figure A.14 – Surface tracking activity along the end arm and corresponding PRPD pattern, recorded on-line

A.3.4.3 Gap type discharges

This activity will occur between bars in the winding overhang or between a bar and the press finger of the stator core. Figure A.15, left, illustrates the degradation resulting from the long term attack by bar-to-bar PD activity. The corresponding PRPD pattern is shown in Figure A.15, right. The main characteristic of gap type discharge activity is a horizontal cloud of PDs of relatively constant amplitude, present in both polarities of the voltage. Here, at least two distinct PD sites are active, represented by two PD levels.

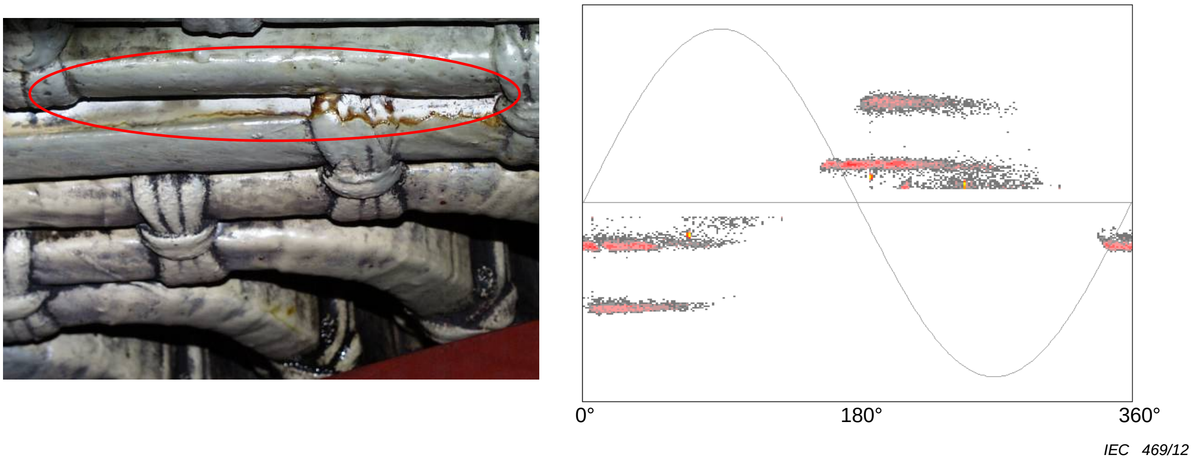


Figure A.15 – Degradation caused by gap type discharges and corresponding PRPD patterns, recorded on-line

A.4 Other complex examples

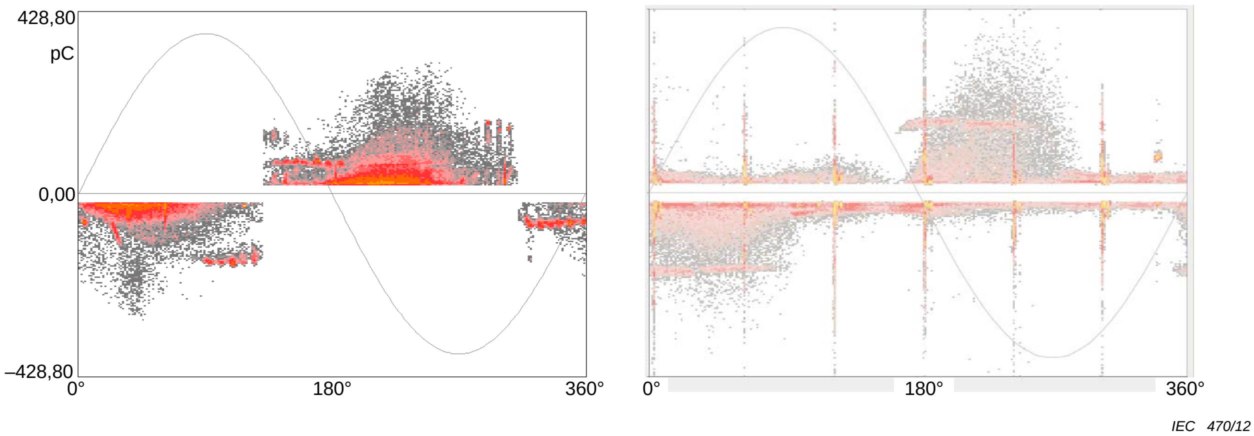


Figure A.16 – PRPD pattern recorded on-line, illustrating multiple PD sources

When possible, visual inspection should be performed to validate PRPD recognition, in order to ensure that the identification resulting from the PRPD pattern is the good one. PRPD recognition can be a useful tool, but the user shall keep in mind that external factors can affect a PRPD pattern. In some cases, superposition of multiple patterns, cross-coupling between phases and noise can be significant, so that identification becomes very difficult. Also, variations in pattern shape, resulting from many external factors, can occur, and the PRPD pattern may vary over the years.

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
Fax: + 41 22 919 03 00
info@iec.ch
www.iec.ch