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TECHNICAL SPECIFICATION

Rotating electrical machines –
Part 27-5: Off-line measurement of partial discharge inception voltage on winding insulation under repetitive impulse voltage

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colour inside

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ROTATING ELECTRICAL MACHINES –

Part 27-5: Off-line measurement of partial discharge inception voltage on winding insulation under repetitive impulse voltage

FOREWORD

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

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

IEC TS 60034-27-5, 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:

Draft TS	Report on voting
2/1955/DTS	2/1962A/RVDTS

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 document 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 document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

The recent development of power electronics technology has led to various power drive systems (PDS) of variable-speed rotating electrical machines. The new influences of PDS on rotating machines are introduced in IEC TS 60034-25 [1][1]. This document points out that electrical insulation of machine winding is exposed to numerous voltage impulses due to the repetitive fast switching of power devices in PDS. The severity of the impulses depends on ratings of converter and machines, converter topology, length of cable between machine and converter, filtering equipment and so on.

IEC 60034-18-41 [2], published in 2014, is the first International Standard which describes design qualification and type tests for Type I (partial discharge free) insulation systems used in converter-fed rotating electrical machines. In this document, both tests require partial discharge (PD) tests with power frequency voltage or impulse excitation. As for PD measurements with impulse excitation, IEC 60034-18-41 cites IEC TS 61934, which provides a technical explanation and several PD measuring methods, in general. For practical test guidance specific to winding insulation of rotating machines, this document was prepared as an off-line measurement of PD inception and extinction voltages during repetitive impulse condition, RPDIV and RPDEV.

[1] Numbers in square brackets refer to the Bibliography

ROTATING ELECTRICAL MACHINES –

Part 27-5: Off-line measurement of partial discharge inception voltage on winding insulation under repetitive impulse voltage

1 Scope

This document provides an off-line measurement method of the partial discharge inception and extinction voltage on winding insulation under repetitive impulse voltage. This document is relevant to rotating machines supplied by a voltage source converter.

2 Normative references

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

IEC 60034-27-1, *Rotating electrical machines – Part 27-1: Off-line partial discharge measurements on the winding insulation*

IEC TS 61934:2011, *Electrical insulating materials and systems – Electrical measurement of partial discharges (PD) under short rise time and repetitive voltage impulses*

IEC TS 62478, *High voltage test techniques – Measurement of partial discharges by electromagnetic and acoustic methods*

3 Terms, definitions, symbols and abbreviated terms

For the purposes of this document, the terms, definitions, symbols and abbreviated terms given in IEC 60034-27-1, IEC TS 61934, and the following apply.

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

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

3.1
partial discharge
PD
localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor

3.2
repetitive partial discharge inception voltage
RPDIV
minimum peak-to-peak impulse voltage at which more than five PD pulses occur on ten voltage impulses of the same peak-to-peak values when the impulse voltage applied to the test object is increased with step-by-step method

Note 1 to entry: This is a mean value for the specified test time and a test arrangement where the voltage applied to the test object is increased with the step-by-step method. Details are mentioned in 5.5.

3.3
repetitive partial discharge extinction voltage
RPDEV
maximum peak-to-peak impulse voltage at which fewer than five PD pulses occur on ten voltage impulses of the same peak-to-peak values when the voltage applied to the test object is decreased with step-by-step method from a higher value at which such discharges are observed

Note 1 to entry: This is a mean value for the specified test time and a test arrangement where the voltage applied to the test object is decreased with the step-by-step method. Details are mentioned in 5.5.

3.4
unipolar impulse
voltage impulse, the polarity of which is either positive or negative

Note 1 to entry: Details are mentioned in 4.2.

3.5
bipolar impulse
voltage impulse, the polarity of which changes alternately from positive to negative or vice versa

3.6
peak-to-peak impulse voltage
$U_{pk/pk}$
maximum numerical value of voltage reached from the lowest value impulse

Note 1 to entry: The definition of peak-to-peak voltage is clarified in Clause 4.

Note 2 to entry: $U_{pk/pk}$ is used for the entire waveform of the impulse including distorted impulses.

3.7
impulse rise time
t_r
time for the voltage to rise from 10 % to 90 % of its final value

3.8
impulse decay time
t_d
time interval between the instants at which the instantaneous values of a triangular impulse decrease from a specified upper value to a specified lower value

3.9
impulse fall time
t_f
time for the voltage of a rectangular impulse to fall from 90 % to 10 % of its initial value

3.10
impulse width
t_w
interval of time between the first and last instants at which the instantaneous value of a single impulse reaches a specified fraction of its impulse magnitude or a specified threshold

3.11
time between two successive impulses
t_{pp}
time between two successive impulses with the same waveform – in a considered set of pulses, for example, for one period

3.12
impulse voltage repetition rate
f_r
average of the inverse of the time between two successive impulses t_{pp}

3.13
train of impulse
sequence of repetitive impulse voltages with the same waveform parameters, including peak-to-peak impulse voltage, rise time, decay time, impulse width, fall time, polarity and time interval between impulses

Note 1 to entry: Details are mentioned in 4.3.

3.14
step-by-step method
SBS method
method of impulse voltage application of trains of repetitive impulse with step-by-step increase and decrease of peak values

Note 1 to entry: Details are mentioned in 4.4.

3.15
U_s
starting applied voltage $U_{pk/pk}$ during step-by-step method

Note 1 to entry: See Figure 16 and Figure 17.

3.16
U_m
maximum applied voltage $U_{pk/pk}$ during step-by-step method

Note 1 to entry: See Figure 16 and Figure 17.

3.17
ΔU
increase or decrease voltage $U_{pk/pk}$ during step-by-step method

Note 1 to entry: See Figure 16 and Figure 17.

3.18
N_p
number of impulses in a train during step-by-step method

Note 1 to entry: See Figure 16.

3.19
t_{ss}
rest time between two trains of impulses with voltage step ΔU during step-by-step method

Note 1 to entry: See Figure 16.

3.20
k
ratio of $U_{pk/pk}$ value of distorted waveform to original $U_{pk/pk}$ at open terminal of an impulse generator

3.21
conditioning
pre-application of conditioning voltage before PD test for stable measurement condition

3.22
ringing
transient oscillation of impulse voltage that is influenced by the circuit impedance

3.23
noise
electric noise caused by thermal white noise from PD detection circuit or impulse generator which may lower PD detection sensitivity

3.24
disturbance
electric and electromagnetic transient impulse from impulse generator or adjacent electric devices which may disturb PD pulse waveform observation

3.25
motorette
special test model used for the evaluation of the electrical insulation systems of random-wound windings

3.26
formette
special test model used for the evaluation of the electrical insulation systems for form-wound windings

3.27
parallel winding
special test winding in which the turn/turn insulation is simulated by at least two electrically isolated conductors wound in parallel, one of which is grounded and the other is energized

4 Repetitive impulse voltages for PD measurement

4.1 General

This document describes RPDIV and RPDEV as repetitive partial discharge inception and extinction voltage of test objects under repetitive impulse voltage. They were first defined in IEC TS 61934 and are redefined in this document. Both RPDIV and RPDEV have two features compared with the conventional PDIV and PDEV under sinusoidal voltage defined in IEC 60034-27-1. The first feature is the clear definition of repetitive impulse voltage with distortion and the second one is 50 % PD occurrence probability.

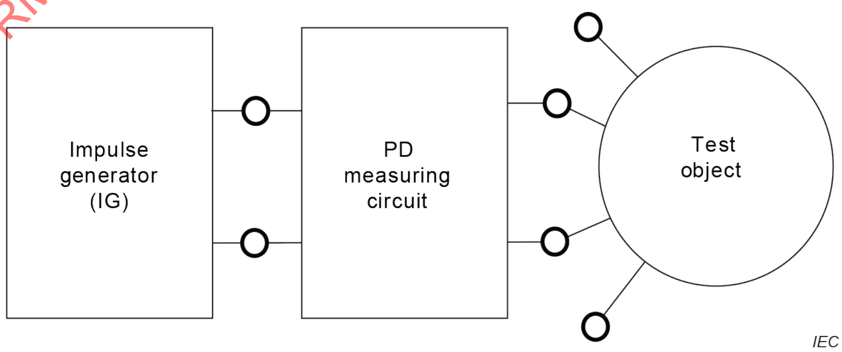


Figure 1 – Block representation of measurement circuit for RPDIV and RPDEV

Figure 1 shows a representative scheme of a measurement circuit for RPDIV and RPDEV as a block diagram. Repetitive impulse voltage from an impulse generator (IG) are mentioned in detail in this Clause 4. PD measuring methods are mentioned in Clause 5. Subclause 6.1 describes test objects of both model samples and complete windings. A four-terminal test object is illustrated in Figure 1 as a complete winding of a three-phase rotating machine with a neutral point terminal. The combination of the possible connections is summarized in Table 2 and Table 3 and in Annex C. PD behaviour reflects the internal voltage inside the winding of the test object mentioned in 4.5. The relation between terminal voltage and internal voltage distribution depends mainly on rise time t_r. For the detection of PD on turn-turn insulation, a short t_r is preferable, as rise time t_r is influenced not only by output from the IG, but also by whole circuit parameters. The detail is discussed in 4.5.

This Clause 4 starts with the waveforms of single impulse voltage at the open terminals of two types of impulse generator: a conventional IG circuit with one switch, and a four-arm (H type) bridge circuit, like a converter itself as mentioned in 4.2.1. The output waveform of the IGs looks like a triangular or rectangular impulse, respectively.

The impulse voltage waveforms are distorted due to test objects with capacitive, inductive and resistive impedance. The distortion can occur through attenuation and dispersion, but also as a result of reflection, resonance and cross-coupling phenomena. Three typical distortions of single impulse waveform are discussed in 4.2.2. Next is the introduction of a "train of impulse" which characterizes the repetition of a single impulse as mentioned in 4.3. Finally, the step-by-step (SBS) increase and decrease of the train of repetitive impulses is mentioned in 4.4. Many different types of impulse waveforms are presented in Clause 4. In practice the impulse generators (IG) producing waveforms in Figure 12 and Figure 16 are the most common.

4.2 Waveform of single impulse voltage

4.2.1 Waveform at impulse generator terminal without test object

The waveform of a single impulse depends on the impulse generator and the test circuit conditions. Impulse generators (IG) used in this document may be classified into two types of circuit.

The first type of IG consists of capacitor C, switch S and an output impedance, resistance R and inductance L as shown in Figure 2. The left-hand side is a charging circuit and the right-hand side is an output terminal. It is noted that the capacitor is regarded as a current source for transient phenomena rather than being a voltage source. Historically, gap discharge between metal electrodes with a trigger was utilized for a long time as switch S. Today, however, high voltage power devices are commonly used as the switch, such as a thyristor, MOSFET, IGBT. When switch S is closed after charging the capacitor C, a triangular unipolar impulse appears at open terminals of the impulse generator as shown in Figure 3. The rise time t_r depends mainly on switching characteristics of the power device and resistance of the test object in series. The decay time t_d depends on resistance R. Without a load or test object, t_d is longer than t_r and terminal voltage appears step-like. With a test object, t_d becomes shorter, and impulse becomes a familiar triangular waveform. The waveform becomes a unipolar impulse with the same polarity as the capacitor. If impulses with both positive and negative polarity are needed for bipolar waveforms, a cascade of the circuit in Figure 2 and the additional switch circuit for polarity change may be necessary.

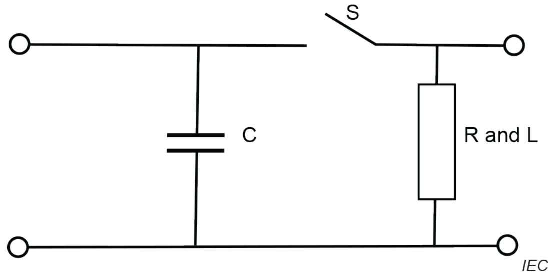


Figure 2 – Simplified impulse generator (IG) circuit with a single switch S

The repetition rate of the impulse may depend on the charging speed of the capacitor in IG, after the first impulse. Figure 4 shows two impulses at open terminal of an IG with a single switch. The time interval between the start of two consecutive impulses is defined as t_{pp}, the inverse of which is the repetition frequency.

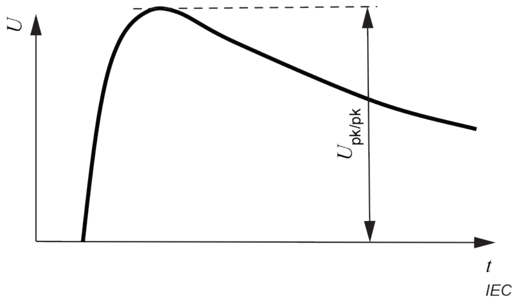


Figure 3 – Output voltage at open terminal of IG with single switch

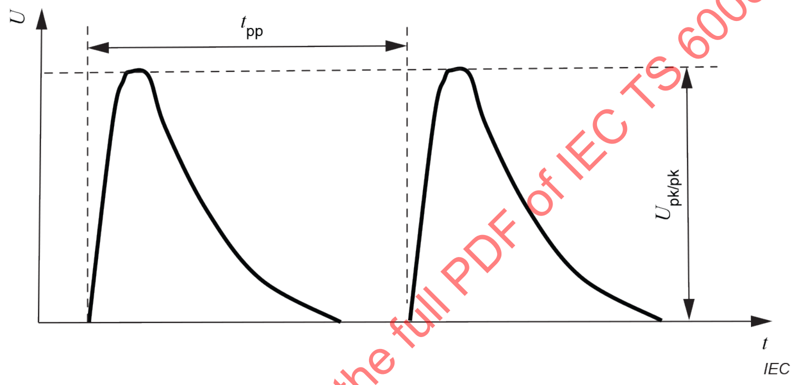


Figure 4 – Two impulses at open terminal of IG with single switch

The other type of IG circuit consists of a so-called four-arm (or six-arm) bridge circuit of power devices, similar to a converter, as shown in Figure 5. On the left-hand side is a charging circuit and on the right-hand side is the output terminal. High voltage power devices such as IGBT are used as switch. According to the open/close combination of four switches S1, S2, S3 and S4, positive or negative rectangular impulses appear at the output terminal.

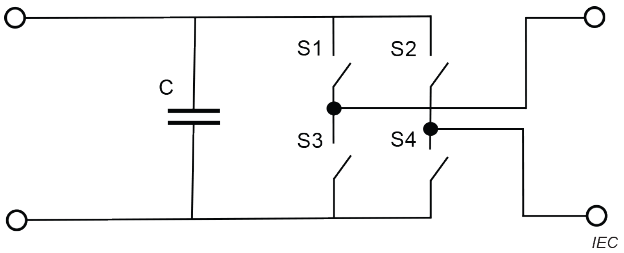
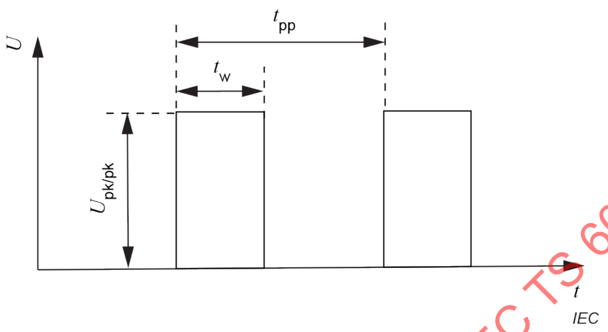


Figure 5 – Simplified IG circuit with four-arm (switch) bridge circuit

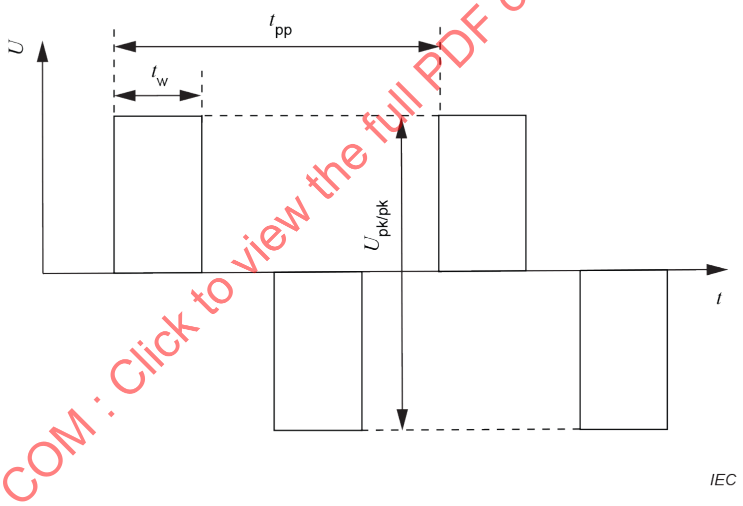
The rise time t_r and fall time t_f of the rectangular voltage depend mainly on switch-on and -off characteristics of the power device used. Although t_r and t_f are almost in the same range, they should be treated separately. As regards the distortions mentioned in 4.2.2, these values can also influence the waveform.

With gate signals of suitable timing, a two-level pulse width modulation (PWM) waveform will appear at the output terminal. For PD measurement, periodic gate signals lead to periodic repetitive impulse voltage at open terminals. With a four-arm (or more) bridge circuit of power devices, both positive and negative rectangular voltage impulse can be created as desired with the appropriate gate signals. Figure 6 a) and Figure 6 b) show both positive/positive unipolar and positive/negative alternating impulses, respectively. For positive/positive unipolar impulses, $U_{pk/pk}$ and t_{pp} can be defined in the same manner shown in Figure 4.

In the case of positive/negative alternating impulses, a set of positive/negative alternating impulses should be treated as one bipolar impulse for PD detection, unless the time between two successive positive and negative impulses is long enough to neglect the electrostatic influence of the preceding impulse on the next one. $U_{pk/pk}$ should be measured from negative peak to positive peak values, and t_{pp} should be measured between successive bipolar impulses.



a) Two positive unipolar rectangular impulses



b) Alternating unipolar rectangular impulse (bipolar impulse)

Figure 6 – Output voltages at open terminal of four-arm bridge circuit

4.2.2 Typical distortions of impulse waveform at the terminals of test object

It is emphasized that with most test objects, the impulse voltage waveform is distorted due to the circuit impedance of the entire test circuit, including IG, measuring circuit and test object. The reason is that test objects in this document may have a wide variety of impedance. The typical distortions may be classified into three patterns. The effect of the rotor on the waveform distortion is also introduced.

a) Increase of rise time and decrease of peak voltage

   Figure 7 and Figure 8 show the increase of rise time and decrease of peak voltage to triangular and rectangular impulses, respectively, where dotted lines show the deformed waveforms.

   When the test object is a complete winding and the capacitance between the winding and ground is large, the rise time of the impulse voltage applied to the test object may become longer than the original rise time at the open terminal of the IG. This phenomenon may occur when the IG cannot provide enough capacitive current for the test object to generate a steep-fronted voltage rise. It might be overcome by increasing the current capacity and output impedance of the impulse generator.

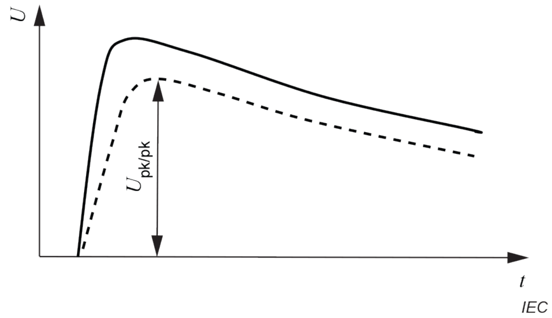


Figure 7 – Increase of rise time and decrease of peak voltage of triangular impulse

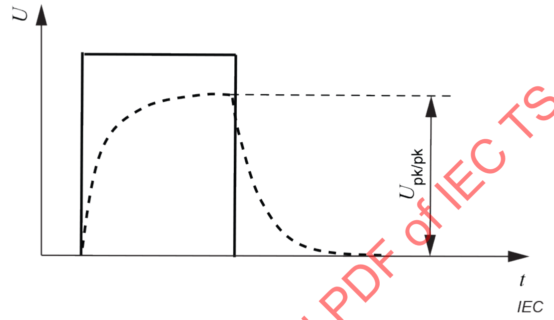


Figure 8 – Increase of rise time and decrease of peak voltage of rectangular impulse

b) Overshoot of peak and following fast oscillation (ringing)

Figure 9 and Figure 10 show the overshoot of the voltage peak, followed by fast oscillation for triangular and rectangular impulses, respectively. The phenomenon is often observed in real test objects and is called "ringing", since the circuit includes both stray capacitance and inductive factors. Peak-to-peak impulse voltage $U_{pk/pk}$ should be measured from maximum peak of positive impulse to minimum peak of negative impulse of observed distorted waveform. Figure 11 shows an example of an observed waveform for repetitive rectangular impulses.

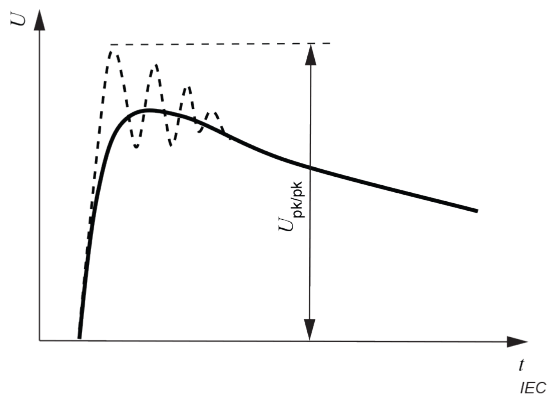


Figure 9 – Overshoot of peak and following fast oscillation of triangular impulse

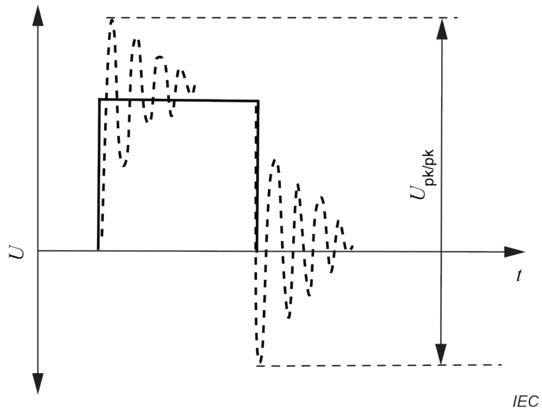


Figure 10 – Overshoot of peak and following fast oscillation of rectangular impulse

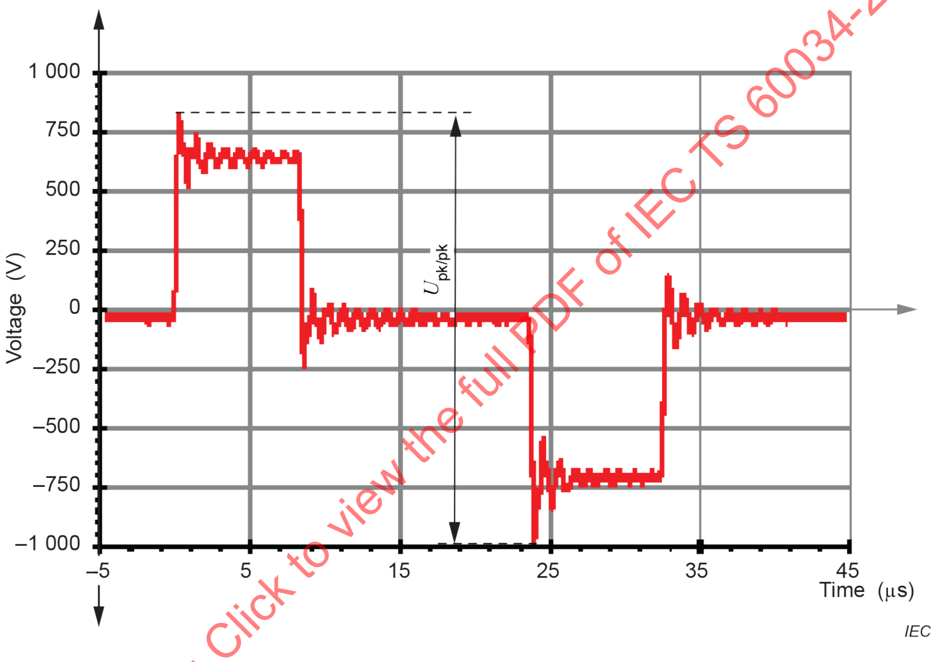


Figure 11 – Typical "ringing" observed during bipolar rectangular voltage test

c) Slow oscillating decay (reverse overshoot)

Figure 12 and Figure 13 show the slow oscillating decay of triangular and rectangular impulses, respectively. When the inductance of the test object causes a slow oscillation during/after decay, a positive unipolar impulse may become a bipolar one, and the peak-to-peak voltage of impulse increases unintentionally. $U_{pk/pk}$ should be measured from the top of peak to the reverse peak of oscillation as shown in Figure 12 and Figure 13. When the oscillation does not reach negative value, $U_{pk/pk}$ should be measured from zero to positive peak. It is also noted that impulse width t_w decreases greatly.

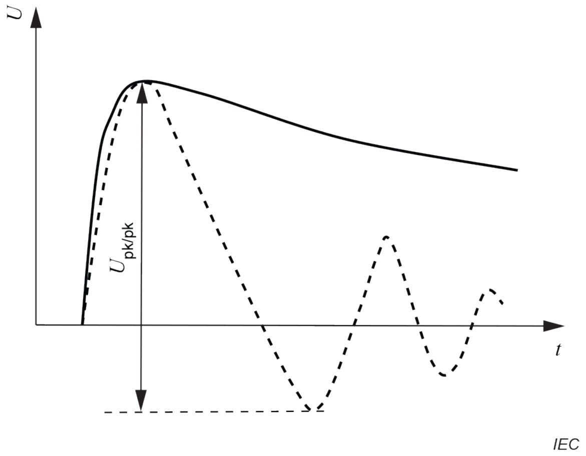


Figure 12 – Slow oscillating decay of triangular impulse

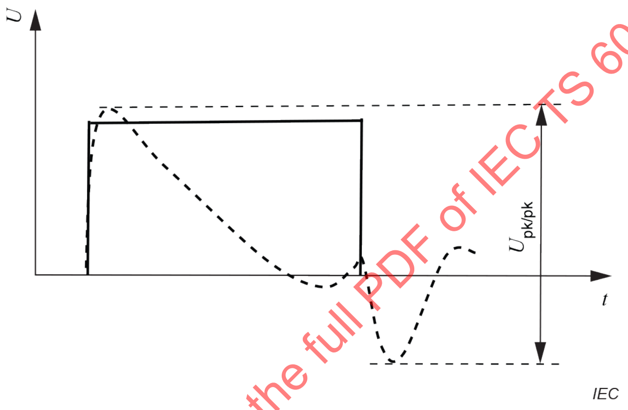


Figure 13 – Slow oscillating decay of rectangular impulse

As shown in Figure 13, the slow oscillation of the first impulse may be superposed on that of the following impulses. When the oscillation is too slow compared with impulse waveform at open terminal, multiple superpositions may result in complicated waveforms. Accordingly, the recording of real impulse waveforms during PD measurement is strongly recommended.

d) Effect of rotor

Recently, the influence of a rotor on the internal voltage distribution of stator winding has been reported [3]. Unlike sinusoidal voltage, high-frequency Fourier components of the impulse voltage surge are sensitive to the existence of magnetic flux passing through the rotor. According to [3] the waveform of the impulse may be strongly distorted with a rotor. The distorted waveform or $U_{pk/pk}$ can change the PD inception voltage. These effects depend on the kinds and structures of rotors of three-phase AC machines. Therefore, the presence of a rotor during PD measurement shall be reported with the recording of real impulse waveforms.

4.3 Train of single impulse voltage

Power switching devices such as IGBTs or MOSFETs used in impulse generators are driven with a gate signal, which means the repetition parameters may be controllable.

In this Subclause 4.3, the concept of "train of impulse" is described using rectangular impulses, while the concept can be applied for both triangular and rectangular impulses. The output of a PWM converter consists of a set of rectangular voltage impulses, the fundamental frequency component of which determines the speed of a three-phase AC machine. For PD inception voltage measurement, it is natural to use such repetitive impulses rather than a single impulse. The pattern of PWM changes often in operation; it seems appropriate to define a train of a plural number of single impulse voltages with a suitable time interval.

In this document, a "train of single impulses" is defined with the following parameters. As shown in Figure 14, the train of either positive or negative unipolar impulses is characterized with the number N_p of repetitive single impulses with same waveform and with the same t_{pp}. Clearly t_{pp} should be longer than the width of single impulse t_w. Repetition frequency f_r used in several publications is the inverse of t_{pp}. Figure 15 shows the train of bipolar impulses at the output terminal, where it also involves alternating unipolar impulses as mentioned in 4.2.1. With test objects, the waveforms of Figure 14 and Figure 15 may be distorted as shown in Figure 12 and Figure 13. The train of positive unipolar impulse can be changed to a train of bipolar impulse. Accordingly, $U_{pk/pk}$ shall be measured on the distorted impulse waveform, not the original waveform at open terminal of an impulse generator.

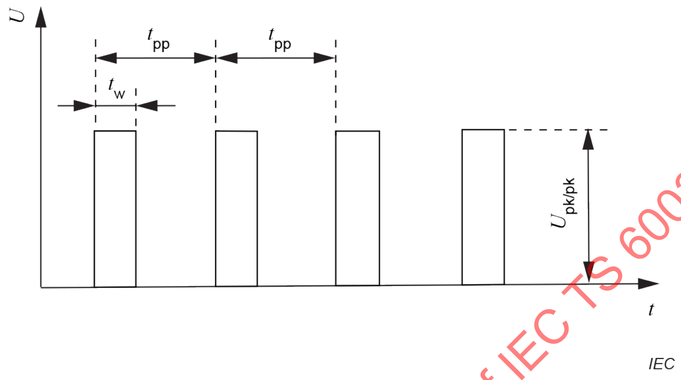


Figure 14 – Schematic representation of train parameters of positive unipolar impulses

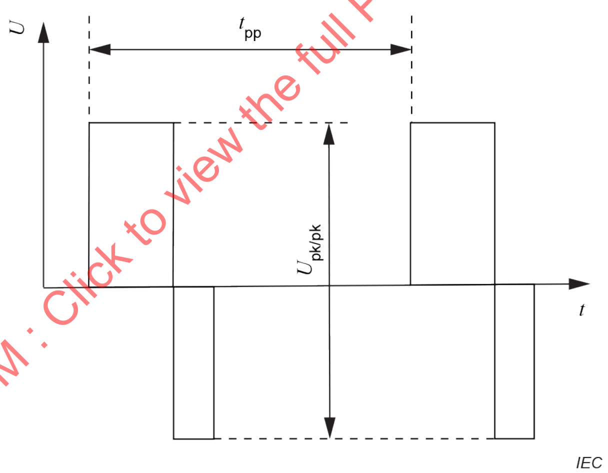


Figure 15 – Schematic representation of train parameters of bipolar impulses

4.4 Step-by-step voltage increase and decrease using trains of single impulse voltage

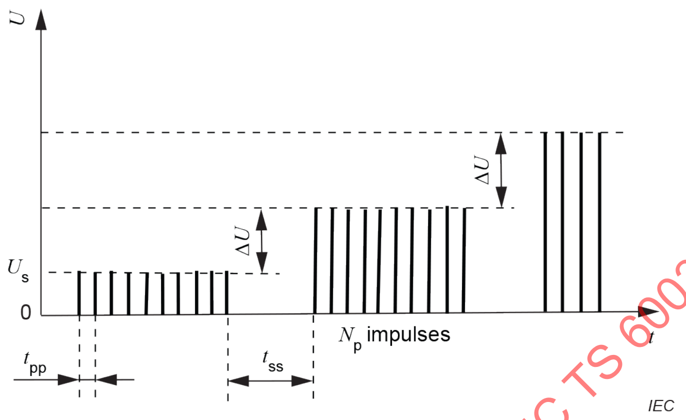
In this document, the step-by-step (SBS) method means the set of trains of single impulse voltage with "SBS parameters" and "train parameters" mentioned in 4.3. SBS parameters are given as follows:

a) start voltage U_s and maximum voltage U_m;

b) step voltage increase or decrease ΔU between successive trains;

c) rest time t_{ss} between two trains of impulses with voltage step ΔU.

Figure 16 shows an example of an SBS pattern for RPDIV measurement for positive unipolar impulse without distortion. For the measurement of RPDIV, the SBS pattern should start from U_s to U_m with step voltage increase ΔU and rest time t_{ss}. As shown in Figure 17, both RPDIV and RPDEV are obtained in one test procedure, when the test voltage increases from U_s to U_m, and decreases from U_m to U_s. While the SBS pattern may be generated manually, presetting of automatic SBS patterns may be possible with the recent IGs. Minimum values of both t_{pp} and t_{ss} depend on the specification of the IG used. Since U_s < RPDIV and RPDEV < U_m, preliminary tests to set up the suitable values of U_s and U_m may be beneficial. However, U_m may be limited if the application of higher voltage might damage the insulation system. The other possible SBS pattern is discussed in Annex D.

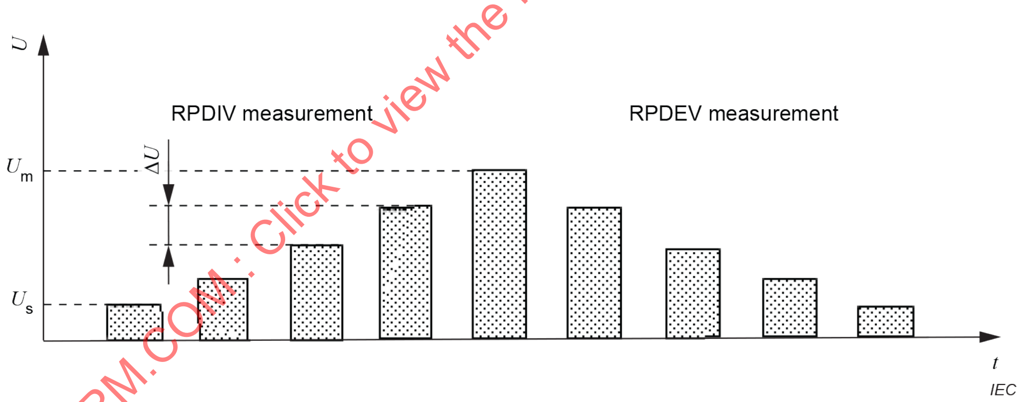


Key

t_{pp} time interval between successive impulses with same peak value

t_{ss} rest time between two trains of impulses with voltage step ΔU

Figure 16 – SBS parameters of positive unipolar impulses



Key

Shadow blocks show trains of unipolar impulses

Figure 17 – SBS voltage pattern of positive unipolar impulses for RPDIV and RPDEV

The maximum applied voltage U_m may be chosen arbitrarily for research, and it is usually higher than the expected RPDIV and RPDEV values. For qualification and/or verification purposes of complete windings, however, U_m may be chosen as a certain value. When lower than 50 % PD occurrence is observed at U_m, the RPDIV may be judged as being higher than the expected value, while the RPDEV cannot be obtained. If higher than 50 % PD occurrence is observed below U_m, the SBS voltage may be stopped and reduced to measure RPDEV.

In practice the voltage distortion of the impulse waveform is often observed, as mentioned in 4.2. Especially in the case of bipolar oscillation of unipolar impulses as shown in Figure 12 and Figure 13, the SBS patterns of positive unipolar impulses may become bipolar. If the IG can be set to automate the SBS pattern of unipolar voltage increase ΔU without the test object as shown in Figure 16, then the distorted SBS pattern becomes as shown in Figure 18. U_s may change as kU_s and $U_{pk/pk}$ of the second train in Figure 18 becomes $k(U_s + \Delta U)$, where k is the ratio of $U_{pk/pk}$ value of distorted waveform to original $U_{pk/pk}$. It is noted that the ratio k is determined only with distributed impedance of the measuring circuit.

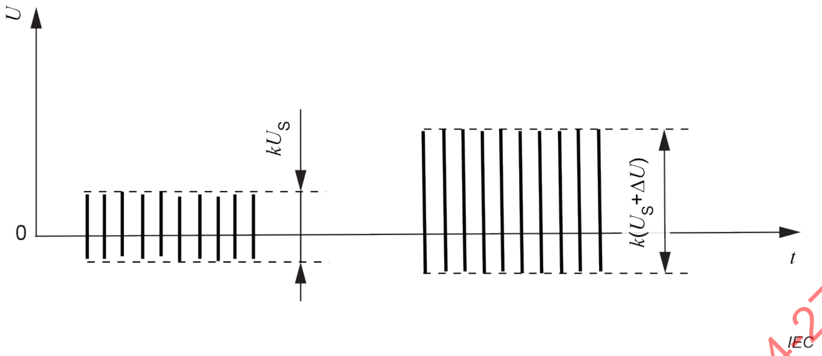


Figure 18 – SBS voltage pattern of bipolarly distorted positive unipolar impulse

Figure 19 shows the SBS pattern of bipolar impulses (N_p = 5) including an alternating unipolar impulse, as shown in Figure 6 b). It is noted that U_s, U_m and ΔU should be measured from the negative peak to the positive peak values as $U_{pk/pk}$, while t_{pp}, t_{ss} and N_p are measured in the same way as in Figure 16.

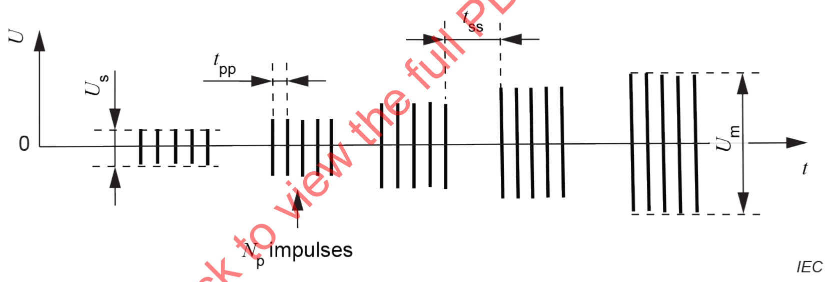
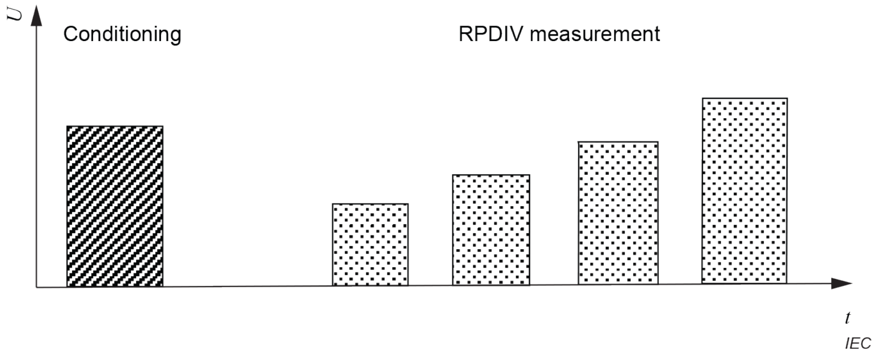


Figure 19 – SBS voltage increase of bipolar impulses

The so-called "voltage conditioning" effect may reduce the variability in RPDIV and RPDEV. High voltage is applied at a certain time on the test object before PD inception voltage measurement. This technique has been used for a long time for PDIV measurement with sinusoidal voltage application. Figure 20 shows a representative scheme for the conditioning procedure before SBS measurement. The conditioning voltage, unipolar or bipolar, conditioning time and rest time between conditioning and start of measurement should be reported, if applied. If not applied, the first measurement data should be omitted.



Key

Shadow blocks show trains of unipolar/bipolar impulses

Figure 20 – Representative scheme of conditioning procedure before RPDIV measurement

Table 1 shows the parameters of repetitive impulse for RPDIV/RPDEV measurement, typical range of the parameters and example values reported [2],[4]. Values in examples column "a*" correspond to values of parameters for the impulse PD measurement of turn/turn insulation mentioned in IEC 60034-18-41:2014 and IEC 60034-18-41:2014/AMD1:2019, Annex B. Example "b*" corresponds to values used in a round-robin test of random-wound motors [4]. These values may be useful for preliminary setup of impulse generators. It is emphasized that only $U_{pk/pk}$ values, the measured terminal voltage at the test object should be used for the calculation of RPDIV and RPDEV.

Table 1 – Typical ranges of impulse voltage parameters at terminal of test object to be reported

Kind of parameter	Characteristics	Typical range of values	Examples	
			a*	b*
Single impulse	Shape	Triangular or rectangular	Triangular	Triangular
	Polarity	Positive or negative unipolar or bipolar	Positive or negative unipolar	Negative unipolar
	Impulse rise time t_r	0,05 µs to 2,0 µs	0,1 µs to 0,5 µs	0,14 µs 1,24 µs
	Impulse decay time t_d	5 µs to 100 µs	-	-
	Impulse width t_w	1 µs to 50 µs	> 5 µs	2,6 µs to 20,3 µs
	fall time of rectangular t_f	0,05 µs to 2,0 µs	-	-
	Type of distortion	a, b, c	Visual judge	b and c
Train of impulses	Number of impulse N_p	5 to 100	-	10
	Time interval between impulses t_{pp}	> 100 µs	-	100 ms
	Pattern of polarity	Unipolar or bipolar	-	Negative constant
SBS test	Start voltage U_s	5 % to 50 % of U_m	-	2 kV
	Maximum voltage U_m	2 kV to 20 kV	-	5 kV
	ΔU	1 % to 10 % of U_m	-	100 V
	t_{ss}	10 ms to 2 000 ms	-	500 ms

Kind of parameter	Characteristics	Typical range of values	Examples	
			a*	b*
Optional parameters	Rotor	Kind of rotor, if any	-	No rotor
	Conditioning	Voltage and application time, if any	-	No conditioning

Key

Values in examples column "a*" correspond to values of parameters for the impulse PD measurement of turn/turn insulation mentioned in IEC 60034-18-41:2014 and IEC 60034-18-41:2014/AMD1:2019 [2], Annex B.

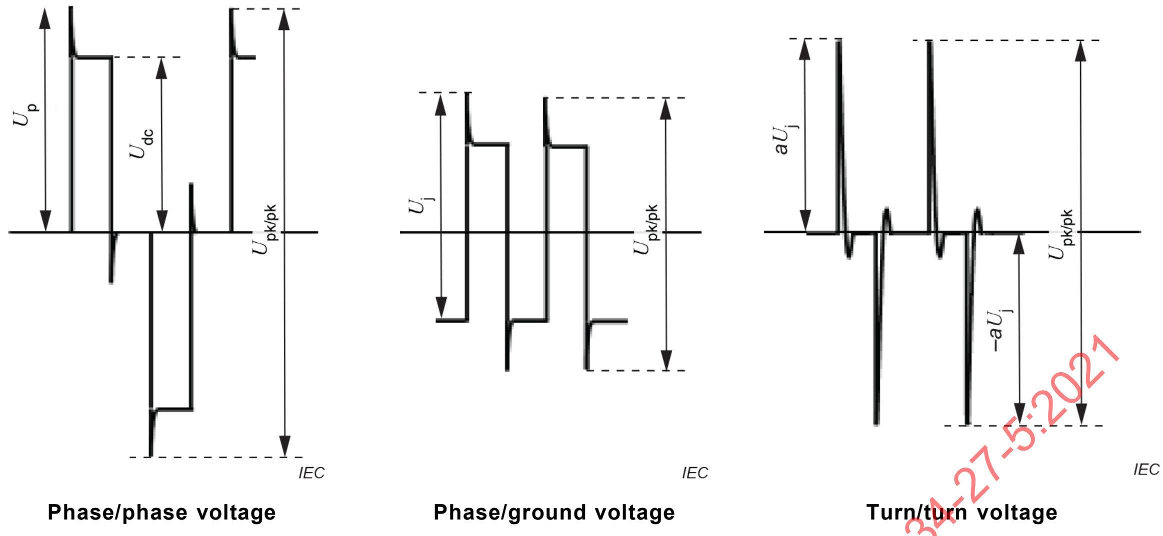
Example "b*" corresponds to values used in a round-robin test of random-wound motors [4].

4.5 Impulse voltage distribution inside rotating machines

The difference of voltage distribution of each portion inside rotating machines should be taken into account before PD measurement of complete winding in 6.1.3. Figure 21 shows a schematic representation of phase/phase, phase/ground and turn/turn voltages appearing at an AC rotating machine fed from a two-level converter. Figure 21 is based on Figure B.3 of IEC 60034-18-41:2014 [2]. In Figure 21, U_{p}, U_{dc} and U_{j} represent peak voltage, steady state impulse and jump voltage, respectively. The letter "a" represents the fraction of voltage stressing the turn/turn insulation. When the phase/ground voltage $U_{\mathrm{pk/pk}}$ has both shorter rising and falling edges, the gradient of which leads to higher positive or negative peaks on turn/turn insulation. In other words, the fraction "a" become higher with shorter rise time and fall time of square waveform of phase/ground voltage, which leads to higher $U_{\mathrm{pk/pk}}$ of turn/turn insulation. For the detailed explanation, please refer to the original document [2]. The connection type between an impulse generator and terminals of AC machine may also influence the difference of voltage distribution as mentioned in 6.1.3 and Annex C.

Using additional probes in the winding, many researchers have reported for random-wound windings that voltage stress in the first coils is the highest and that this depends on the rise time of the impulse applied. Figure 7 of IEC 60034-18-41:2014 [2] shows the worst case scenario of turn/turn voltage in the first coil against rise time in a variety of random wound stators. When the rise time is 0,3 μs, 70 % of the total voltage is concentrated at turn/turn insulation in the first coil. Therefore, IEC 60034-18-41 recommends having 0,3 μs in rise time of impulse voltage for PD measurement of turn/turn insulation.

Since PD activity is strongly influenced by the internal voltage distribution, the measured values of RPDIV and RPDEV should be interpreted carefully according to the parameters in Table 1, the rise time t_{r} and fall time t_{f} especially.



NOTE This is a schematic representation and not scaled for phase/phase, phase/ground and turn/turn voltages. The letter "a" represents the fraction of voltage stressing the turn/turn insulation.

Figure 21 – Schematic representation of phase/phase, phase/ground and turn/turn voltages of the winding of a rotating machine fed from a two-level converter [2]

5 PD measurement methods with impulse voltage

5.1 General

IEC TS 61934 provides several electrical PD measuring methods. Clause 5 describes practical electrical and nonelectrical methods for converter-fed rotating machines. Then, the effect of disturbances and thresholds are mentioned.

Measuring PD inception voltage under repetitive impulse voltage stress normally renders different results compared to those measurements defined in IEC 60034-27-1. This is due to the fact that the impulse voltage distribution across the various parts of the winding insulation is different from that under sinusoidal voltage stress. Some parts of the insulation may be stressed equally, while other parts may be stressed to a higher and others to a lower extent.

The oscilloscope and the high voltage probe used to measure the voltage and PD pulse should have a bandwidth exceeding that of the impulse, evaluated approximately as the reciprocal of the rise time of the impulse.

5.2 Electrical PD measurements

5.2.1 General

IEC TS 61934 presents the following electrical PD detection devices.

5.2.2 Coupling capacitor with higher order analogue filter

A coupling capacitor with a voltage rating exceeding that of the expected applied impulse voltage together with a filter that strongly attenuates the test voltage impulses can be used as shown in Figure 22. The filter should have at least three poles and special measures to inhibit cross coupling of the input signal to the output. The filter can be designed using passive or active filtering technology. The coupling capacitor is connected to the test object high-voltage terminal. Figure 23 reports an example of frequency spectra of PD pulse and impulse voltage before and after filtering for an eighth order filter.

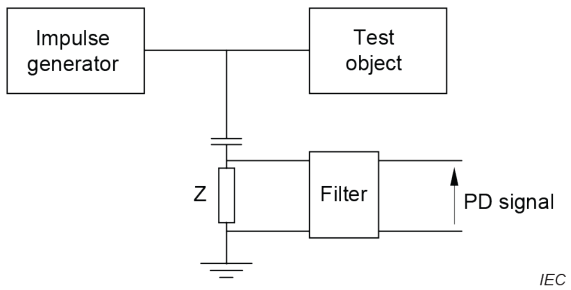
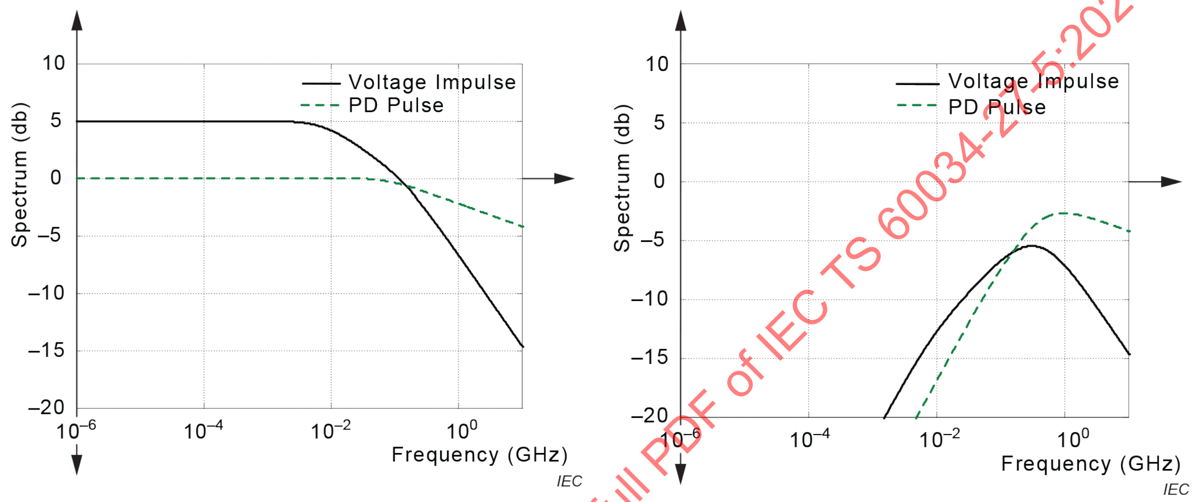


Figure 22 – Coupling capacitor with higher order analogue filter



NOTE Impulse voltage rise-time 50 ns, PD pulse rise-time 2 ns, eighth order filter with filter cut-off frequency equal to 500 MHz.

Figure 23 – Example of voltage impulse and PD pulse frequency spectra before (left) and after (right) filtering

5.2.3 HFCT with higher order analogue filter

A high-frequency current transformer (HFCT) together with a filter can be used to detect PD pulses while suppressing the impulse voltage. Note that HFCTs may have a very wide range of upper cut-off frequencies that may affect the performance of this method. The HFCT should have a higher cut-off frequency than the upper limit of PD pulse frequency to get a maximum sensitivity for PD signals. The filter should have at least three poles and special measures to inhibit cross-coupling of the input signal to the output. The filter can be implemented using passive or active filtering technology. The HFCT can be placed over the high-voltage cable between the impulse supply and the test object (Figure 24). In this case, the HFCT should have sufficient electrical insulation to ensure that breakdown and/or partial discharge between the cable and the HFCT does not occur. Alternatively, the HFCT can be connected between the test object and earth (Figure 25). Only low-voltage insulation is then required. The latter arrangement is effective, in general, only if the metallic enclosure of the test object can be isolated from earth.

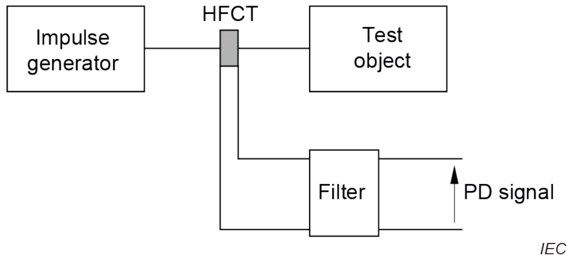


Figure 24 – HFCT between supply and test object with higher order analogue filter

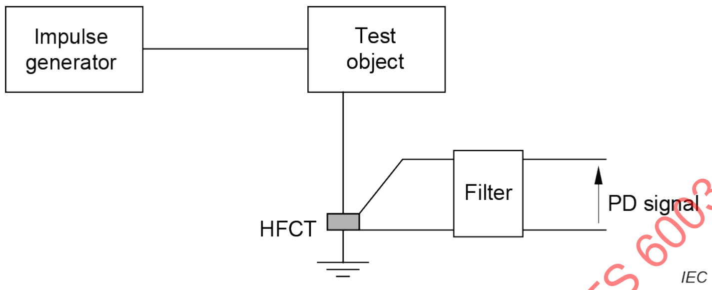


Figure 25 – HFCT between test object and earth with higher order analogue filter

5.2.4 Electromagnetic couplers

Antenna-type couplers can be used to separate impulses from the supply from PD originating in the test object as shown in Figure 26.

Various antenna-type couplers can be used to detect an electromagnetic signal from the partial discharge site in the test object. For the separation of the PD signal from the impulse voltage, the couplers should have suitable frequency characteristics.

An ultra-wide band (UWB) coupler can detect a PD signal with impulse noise. To suppress the impulse voltage, an electromagnetic near-field coupler with a fixed coupling impedance to the lead from the impulse supply to the test object can be effective.

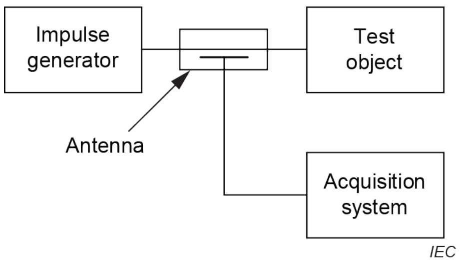


Figure 26 – Circuit using an electromagnetic coupler (for example an antenna) to suppress impulses from the test supply

An alternative electromagnetic coupler can detect the radiated electromagnetic signals propagating through free space from the PD site in the test object (Figure 27). If the antenna has UWB characteristics including a lower frequency component of impulse voltage, a filtering function is necessary to suppress the residual signal inside the acquisition system. Some double-ridged guide antennae (horn antennae) have a cut-off frequency above 0,5 GHz which need no filters. UHF antennae with narrow-band characteristics, the centre frequency of which is higher than those of impulse voltage also do not need a filter for the same reason. Note that the coupling efficiency will depend on the distance between the PD site and the antenna as well as the presence of any metallic shielding between the PD site and the antenna.

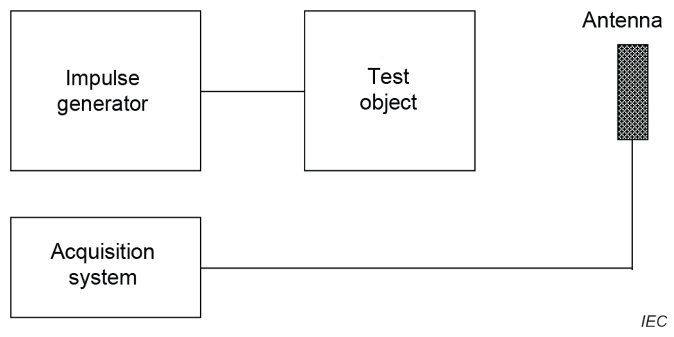


Figure 27 – Circuit using an electromagnetic UHF antenna

Optical measurements of PD have been used mainly on a twisted pair or equivalents in laboratories because of its high PD sensitivity. The optical signal can be detected even with high electromagnetic noise and disturbance. With special conditions such as low air pressure, a glow-like PD around a complete winding can be detected optically. Optical UV sensors such as a photomultiplier tube with flexible optical fibre shall be able to view all parts of the test object.

5.3 Threshold level of PD detection

In general, the PD inception voltage may be measured with any level threshold detection system. Usually the threshold value has been selected to be slightly higher than the noise level. Under higher noise circumstances, a higher threshold value may be selected, which may lead to a higher PD inception voltage. In other words, a higher noise level may lead to less sensitive PD measurements. The ambiguity in the setup of threshold levels has been one of the fundamental problems of PDIV detection. In IEC 60034-27-1 with sinusoidal voltage application, calibration in pico-Coulomb (pC) is recommended for comparison of the noise level between different measuring systems.

In the case of a repetitive impulse voltage, however, pC calibration is not possible because the PD detection frequency is in the VHF or UHF ranges mentioned in 5.2. Instead, a sensitivity check as set out in IEC TS 61934 and/or in IEC TS 62478 is required. Furthermore, "disturbance" means transient induced signals from the impulse generator itself and/or adjacent electric devices. As shown in Figure 28, the disturbance level due to short rise time of the applied impulse itself may often be higher than the thermal noise level and it may disturb PD pulse detection. It is noted that the PD threshold value is higher than the disturbance level and that different threshold values may lead to a different PD inception voltage, as shown in Figure 28. The noise and disturbance levels should be reported.

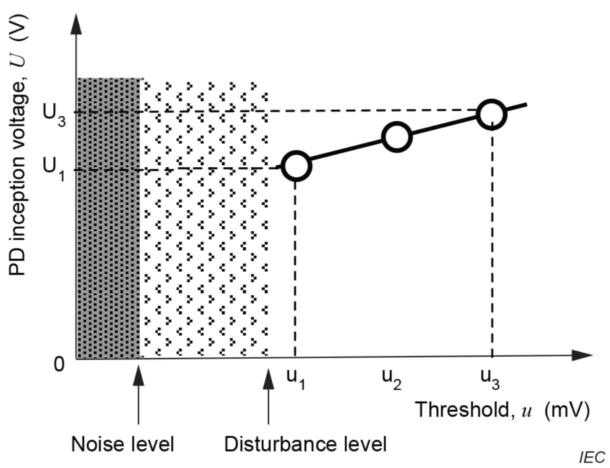


Figure 28 – Schematic representation of noise, disturbance and threshold values

5.4 Measuring system with impulse generator and computer

The low frequency PD detection methods described in IEC 60034-27-1 for sinusoidal test voltage using couplers and electronic circuits have been applied for several decades. The analogue PD signals are detected by couplers and are amplified, filtered, using discriminating analogue or digital electronic circuits.

Figure 29 shows an example diagram of PD measurement in laboratories. The system consists of an impulse generator, a voltage divider, PD sensors (detectors), an oscilloscope and a personal computer (PC) for measurement and data management. It is noted that each unit is connected with a high-voltage analogue line (white), low-voltage analogue line (black) or serial or parallel digital line (grey). Since a series of data of applied repetitive impulse voltages and PD signals are detected in parallel at the same time, sufficient memory capacity may be necessary in the digital oscilloscope or measuring system. An impulse generator with an automatic control unit may be commercially available for practical use. As for the calculation of RPDIV and RPDEV in 5.5 with stored PD pulse data, the computer-assisted system is recommended with the digital oscilloscope. See Annex A.

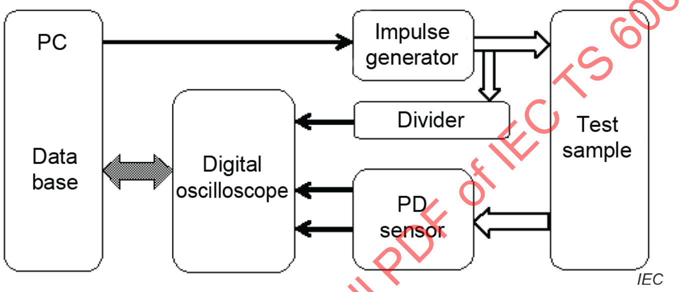


Figure 29 – Example diagram of PD measurements with PC

5.5 Calculation and interpretation of RPDIV and RPDEV

As defined in 3.2 and 3.3, both RPDIV and RPDEV are $U_{pk/pk}$ values at which PD pulses occur against repetitive impulses with a 50 % probability. For example, Figure 30 shows RPDIV and RPDEV based on PD pulse data measured using the SBS method. In this measurement, SBS parameter values are read as N_p = 5, U_s = 1 000 V, U_m = 2 000 V and ΔU = 200 V. Since five impulses are applied in a train, RPDIV is calculated as $U_{pk/pk}$ at which three PD pulses are firstly detected (= 1 800 V) during voltage increase and RPDEV (= 1 600 V) during voltage decrease. Values of RPDIV and RPDEV may be calculated automatically by a computer-assisted system as shown in Figure 29.

Generally, PD activity is unstable around the inception and/or extinction voltage. See Annex A. So RPDIV and RPDEV are recommended with an averaging treatment of unstable PD pulse behaviour. Nevertheless, experience suggests there can still be some scattering. In order to suppress the scattering, improvement of SBS parameters may be effective. For example, a large N_p and low ΔU may lead to more stable results. At least five repeated RPDIV and RPDEV measurements are recommended.

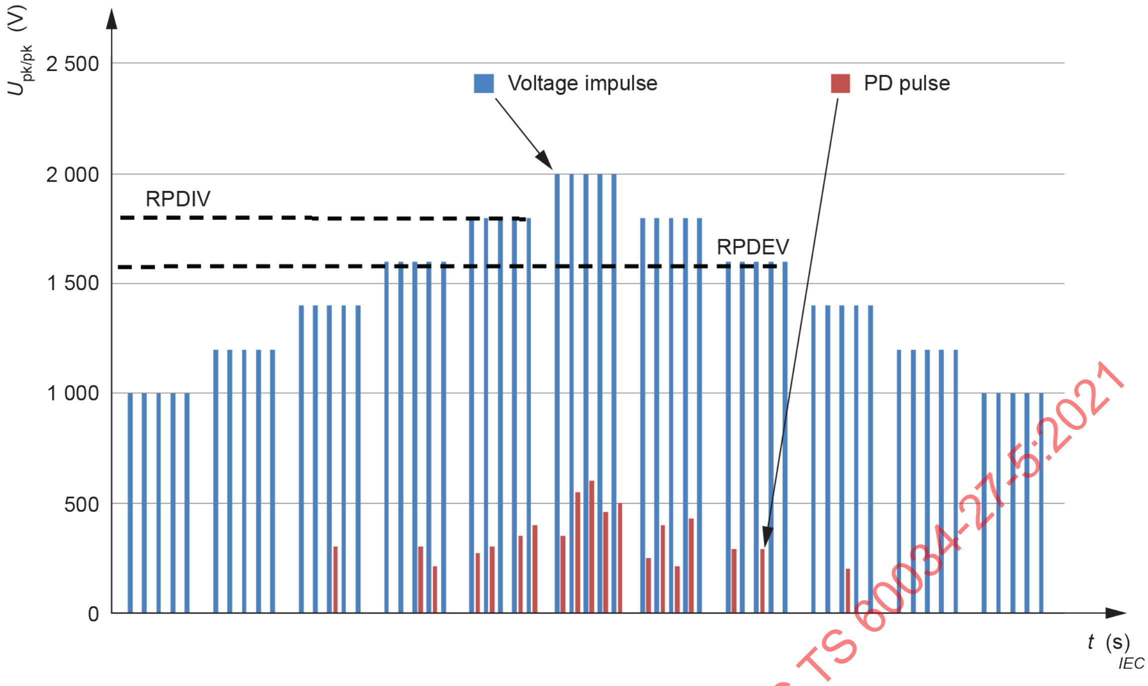


Figure 30 – Example of RPDIV and RPDEV calculation using a 50 % PD probability against repetitive impulse voltage
(Figure 12 of IEC TS 61934:2011, modified)

The minimum values of RPDIV and RPDEV are the most important as a quality control check in mass-production lines. The Weibull distribution plot may be beneficial to confirm the minimum values based on measured data.

RPDIV and RPDEV may depend on the PD detection method and detection parameters, especially the threshold values. Accordingly, noise and disturbance should be measured carefully before the test, and the values should be reported.

RPDIV may be higher than RPDEV, as occurs with PDIV and PDEV measured with sinusoidal voltage.

In the case of inductive test objects such as a mortorette, a formette or a complete winding, a shorter rise time t_r leads to a more uneven voltage distribution, as mentioned in 4.5. That means that PD at turn/turn insulation in the first coil may occur in the case of a very short rise time t_r, which may lower the RPDIV and RPDEV values.

6 Impulse PD test procedure

6.1 Test object

6.1.1 Twisted-pair or equivalent

Twisted pairs of round winding wire have been measured for insulation research of random-wound machine for a long time. There are a lot of publications on PD phenomena using the twisted-pair samples [5] to [10]. For twisted pairs, the RPDIV and RPDEV show the fundamental data for turn-turn insulation design of the machine. Instead of a twisted pair sample, a single contact sample of two wires is also used for more fundamental research of PD phenomena.

Since the capacitance of a twisted pair or the equivalents is small or negligible compared with that of the impulse generators commercially available, the distortion of impulse waveform mentioned in 4.2 is small.

For form-wound winding, the contact of two insulated bars or parallel winding of a rectangular magnet wire wound on a bobbin are typical test objects for the turn-turn insulation.

In the case of the other test objects mentioned in 6.1.2 and in 6.1.3, it is difficult to separate PD signals of each winding portion in general. If the RPDIV and RPDEV of turn/turn insulation are obtained successfully, these simple test models may be useful.

6.1.2 Motorette or formette

Motorettes and formettes have been used as model test objects of insulation systems of random-wound and form-wound machines, respectively. (See IEC 60034-27-1.)

Motorettes and formettes represent phase/phase and phase/ground insulation prepared with the same materials and manufacturing process as real machine manufacturing. Turn/turn insulation can also be represented by use of parallel windings. The applied voltages stressing the model insulation components should reproduce the voltage stress occurring within the complete machine in service.

But it is difficult to determine if the PD is occurring in the turn/turn, phase/ground and/or phase/phase insulation, because the internal voltage within windings is not measured directly and it depends on both internal impedance and waveform of applied impulse voltage. In addition, as the electrical transfer function of the PD from its source inside the insulation system to the measuring point at the coil ends is an unknown R-L-C combination, it is hard to identify the real position of PD source.

6.1.3 Complete winding and connection

RPDIV and RPDEV can be measured on a complete winding of the rotating machine. Unlike model test objects mentioned above, the following precautions are needed.

The capacitance and inductance of a complete winding may cause distortion to the original waveform from the impulse generator, that is, an impulse generator with sufficient capacity is needed. There are many possible connections for RPDIV and RPDEV measurements on three phase windings. A complete winding consists of phase/phase, phase/ground and turn/turn insulation. When RPDIV and RPDEV are obtained on complete windings, it may be difficult to identify the PD site or location. It is well known theoretically and experimentally that turn/turn voltage distribution is uneven along the winding for impulses with short rise time. For machines with a same winding design, the turn/turn voltage in a complete winding may be estimated with data measured on a model machine with additional terminals from conductors inside.

Figure 31 shows a representative scheme of voltage terminals for three-terminal and four-terminal machines. Tested phases are connected to the IG and the PD detector. The remaining phases are connected to the machine's ground. In Figure 31, the potential of the machine frame is floating electrically. Forced grounding of frame (Fr) can affect the internal voltage distribution of the winding.

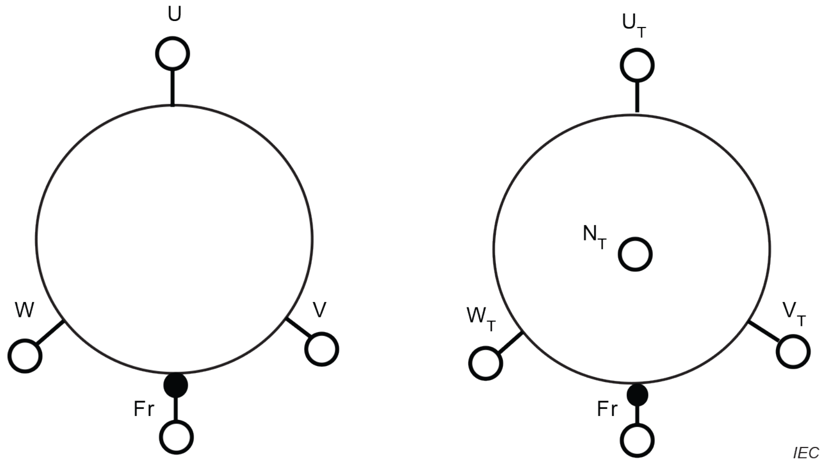


Figure 31 – Representative scheme of voltage terminals for three-terminal machine and four-terminal machine

Possible connections for RPDIV and RPDEV are shown in Table 2 for a three-terminal machine and Table 3 for a four-terminal machine where the neutral Y connection terminal is available, respectively. In each connection phase/phase (p-p), phase/ground (p-g) and turn/turn (t-t) windings have different influences. With any connection, the lowest RPDIV and RPDEV among p-p, p-g and t-t insulation is detected. It is necessary to select the connection carefully for the measurement purpose. Each connection is shown Figure C.1 to Figure C.9.

Table 2 – Connection of complete winding of three-terminal machine

Test type	Terminal voltage				Test portion			Remarks
	U	V	W	Fr	p-p	p-g	t-t	
A	A	G	G	G	*	✓	✓	Mostly recommended for p-g and t-t testing
B	A	A	G	G	*	✓	✓	Recommended (p-p and p-g voltage is applied only between U, V and W, Fr. t-t voltage of the U phase may be lower than that of Test Type A)
C	A	G	G	F	✓	*	*	
D	A	G	F	F	✓	*	*	
E	A	G	F	G	*	✓	✓	
F	A	A	A	G	-	✓	*	

Key

A: voltage applied

G: grounded

F: floating

Fr: frame potential

U: terminal of U phase without neutral terminal

p-p: phase to phase insulation

p-g: phase to ground insulation

t-t: turn to turn insulation

✓: main test portion

*: not main portion but a reduced voltage is applied

Table 3 – Connection of complete winding of four-terminal machine

Test type	Terminal voltage					Test portion			Remarks
	U_T	V_T	W_T	N_T	Fr	p-p	p-g	t-t	
G	A	G	G	G	G	*	*	✓	
H	A	A	G	G	G	*	*	✓	p-p and p-g voltage is applied only between U, V and W, Fr The t-t voltage of the U phase may be lower than connection Type G
I	A	G	G	G	F	*	*	✓	
J	A	G	F	G	F	*	*	✓	
K	A	G	F	G	G	*	*	✓	
L	A	A	A	G	G	*	✓	✓	
M	A	A	A	G	F	*	*	✓	
N	A	F	F	G	F			✓	
G'	A	G	G	F	G	*	✓	✓	Same as Type A
H'	A	A	G	F	G	*	✓	✓	Same as Type B
I'	A	G	G	F	F	✓	*	*	Same as Type C
J'	A	G	F	F	F	✓	*	*	Same as Type D
K'	A	G	F	F	G	*	✓	✓	Same as Type E
L'	A	A	A	F	G		✓	*	Same as Type F

Key

A: voltage applied

G: grounded

F: floating

Fr: frame potential

U_T: terminal of U phase

N_T: potential of neutral terminal

p-p: phase to phase insulation

p-g: phase to ground insulation

t-t: turn to turn insulation

✓: main test portion

*: not main portion but test voltage is applied

6.2 Safety and environment during PD test

6.2.1 Grounding and floating of test objects during tests

Extreme care is necessary after each test, since the full test voltage may still be present on the windings, even if the test instrument has an automatic short circuit applied. Both phases should be discharged to ground potential by appropriate means.

For grounding, the frame and stator core of the rotating machine shall be grounded perfectly. For a floating potential requirement, the whole machine shall be electrically insulated from ground. Grounding is recommended after these tests with voltage floating for safety.

6.2.2 Environment during test

Since the following environmental parameters may influence the PD characteristics, it is recommended to record these environmental data during PD tests for the test report.

Relative humidity has been reported to influence the PD inception in the case of a twisted-pair sample and complete windings [4], [6]. However, the effect of humidity on RPDIV and/or RPDEV may be complex according to several published papers. Therefore, it is recommended that PD tests be performed only in dry condition.

Temperature is also another parameter which may influence PD activity. Room temperature is recommended for testing.

Air pressure will have a major influence on PD activity. For aeronautic applications, special precaution is necessary for converter-fed rotating machine insulation [11]. It is well known that PD occurs around windings easily with glow-like phenomena under low air pressure. Under these conditions, optical detection of PD may be used for RPDIV and RPDEV measurement.

6.3 Test procedure and reports

For RPDIV and RPDEV measurements of test objects, the following process may be undertaken.

1) Selection of test object
2) Selection of test voltage range and necessary impulse generator
3) Selection of PD measuring method
4) Recording of single impulse waveform with/without measuring circuit with test object
5) Adjustment of circuit parameters, if necessary, and recording of the final waveform
6) Noise and disturbance measurement in the measuring circuit
7) Sensitivity check and/or decision of threshold value
8) Decision of all parameter values of single impulse waveform, train and SBS method
9) Adjustment of environmental conditions, if necessary
10) Application of high voltage as conditioning, if necessary
11) Repeated measurement of PD with SBS method
12) Calculation of RPDIV and RPDEV
13) Change the test condition and repeat measurement, if necessary
14) Test report

The following test data shall be attached as a test report.

a) Parameters of single impulse voltage waveform observed at test object terminal
b) Parameters of train of repetitive impulses
c) Parameters of SBS method and voltage conditioning
d) Sensitivity, noise level and threshold for PD detection
e) Type of test object and connection for complete windings
f) Relative humidity, temperature and air pressure during test
g) Waveform recording of impulse voltage and typical PD pulse
h) Other remarks on a kind of rotor used and conditioning parameters, if applied

Annex A
(informative)

Typical PD measurements on a complete winding

Typical PD measurements on a complete winding of aged small motors was performed in a round robin test (RRT) in Japan [4]. Figure A.1 shows a block diagram of the measurement system. Table A.1 shows the values of repetitive impulse parameters.

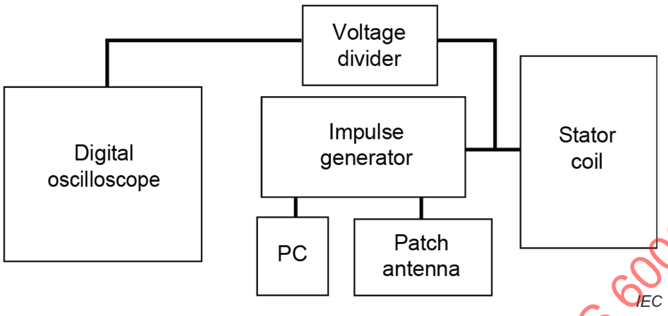


Figure A.1 – Block diagram of PD measurement system used in RRT

Table A.1 – Parameters used in RRT

Characteristic	Value
Rise time	0,14 µs to 1,24 µs
Pulse width	2,6 µs to 20,3 µs
Repetition rate	20 Hz
Shape	Triangular
Polarity	Unipolar (negative)

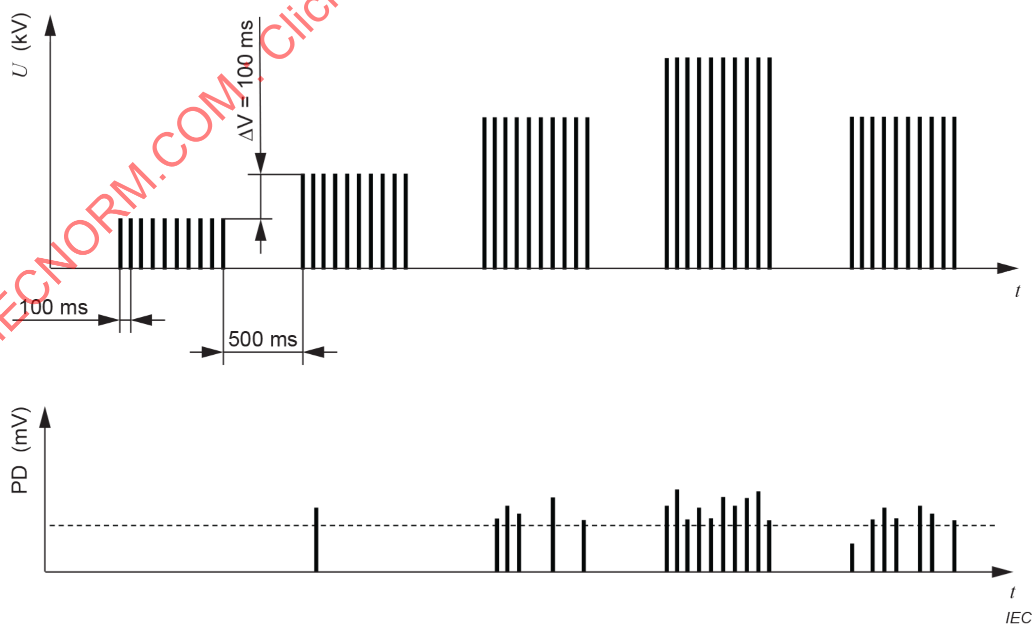


Figure A.2 – Impulse pattern used in RRT and PD inception

Figure A.2 shows the step-by-step increase pattern used in the tests. PD pulses are shown to the applied impulse train. After PD measurements, correction of voltage was done based on Paschen's law for temperature and air pressure. RPDIV values have been calculated according to the definition in 3.4 of IEC TS 61934:2011. The dotted line in Figure A.2 shows threshold voltage in mV.