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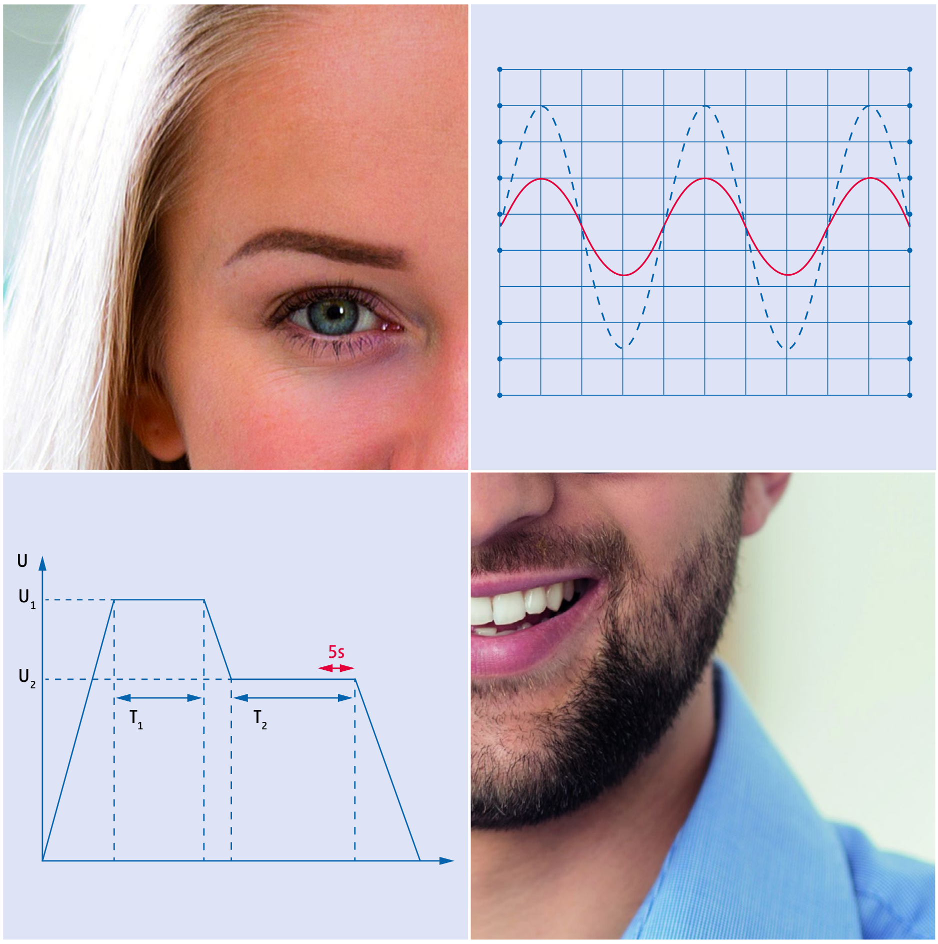
General information

General information regarding partial discharge measurements on Power Electronic Capacitors



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ZVEI e. V.
Electro and Digital Industry Association
Power Capacitors Division
Lyoner Straße 9
60528 Frankfurt am Main

Phone: +49 69 6302-251
Fax: +49 69 6302-407
E-Mail: starkstromkondensatoren@zvei.org
www.zvei.org

Responsible:

Dr. Marcus Dietrich	ZVEI

Authors:

Olaf Rudolph	Beluk
Dr. Volker Geitner	ELECTRONICON Kondensatoren
Thomas Behne	ELECTRONICON Kondensatoren
Helmut Popp	ELECTRONICON Kondensatoren
Erik Winkelmann	Highvolt
Dr. Rainer Weber	Vishay Electronic
Simon Wegler	Vishay Electronic
Ronald Hänssler	TDK Electronics
Angel Sanchez	TDK Electronics
Maria Arribere	TDK Electronics

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1 Introduction

The purpose of this guide is to present a procedure for the partial discharge measurements between terminals and case on Power Electronic Capacitors with a combined DC + AC voltage.

2 Definition of partial discharge

Internal partial discharges (PD) are localized electrical discharges caused by high electrical field strength, which only partially bridge an insulation system between conductors. PD appears predominantly in layered insulation systems composed of different dielectric materials, gas-filled voids, or small particle-inclusions in all types of solid, liquid, or mixed insulation systems. Layered insulation systems containing materials with different permitivities can be particularly problematic. Repetitive partial discharges can result in accelerated aging and early breakdown of the insulation. Therefore, PD measurements and limits are often part of technical specifications for Power Electronic Capacitors. Such measurements are intended to prove the long term stability of insulation systems.

The following standards define typical measuring procedures and application related PD requirements:

- IEC 61287-1 [1] „Railway Applications – Power Converters installed on board rolling stock“
  - 1,1 U_m PD-level < 10 pC

- IEC 61800-5-1 [2] „Adjustable speed electrical power drive systems”
  - 1,5 U_m PD-level < 10 pC

A basic introduction to the theory and measurement of partial discharge in low voltage systems can be found in [3]. The principles and theory described in [3] can also be applied to Power Electronic Capacitors with voltages above 1000 V.

3 Types of partial discharge

There are 2 types of partial discharge measurements on large Power Electronic Capacitors which have to be taken into account:

- PD measurements on the primary, internal capacitance (terminal to terminal)
- PD measurements on the insulation system between internal conductors and the capacitor housing (terminal to case).

4 Parameters used for partial discharge tests

Measurement of partial discharge cannot be done directly because the discharges occur internally in the insulation system and are in series with other capacitances. Therefore, a quantity called apparent charge is measured instead and used to define the results of PD measurements on the device under test (DUT). This measurement method limits the accurate measurement of PD to smaller capacitances (up to a few microfarads).

The problem is related to the signal-to-noise ratio (SNR). The charge stored on the capacitor plates can be thought of as the noise in this case and the signal is generated by PD in the insulation system. During terminal to terminal PD testing, the capacitor contains up to 141 microcoulombs per microfarad of capacitance at 100 V_{RMS} ($Q = C \cdot U$). However, most Power Electronic Capacitors have significantly higher capacitance values ranging up to several millifarads. In this range, the maximum charge stored in the DUT can be several hundred millicoulombs at 100 V_{RMS}. This results in a typical PD signal (10 or 50 pC) which is a minimum of 10 magnitudes lower than the noise (stored charge in the capacitor). PD measuring systems are designed to improve the SNR but there are practical limits which must be accepted. Consequently, terminal to terminal PD measurements are only possible on smaller capacitors.

Most Power Electronic Capacitors have a capacitance between the terminals and case in the nanofarad range. For such capacitances, PD measurements are possible because the SNR is significantly higher. For example, the maximum charge at 100 V_{RMS} for a 10 nF capacitance is roughly 4 magnitudes higher than the usual PD limit of 10 pC. However, even this measurement can be complex and of limited reproducibility. Parameters including but not limited to the capacitor size, design, rated voltage (AC, DC + AC, amplitude), and temperature all influence the results and can make comparing PD values difficult. For accurate measurements, extremely sensitive PD measurement systems combined with a host of additional PD-free devices are required (reference capacitor, high voltage power source, cables, faraday cage with bushings, etc.).

5 Current situation of partial discharge requirements for Power Electronics Capacitors

PD measurements on large Power Electronic Capacitors at high voltages with low specified PD limits are of questionable relevance, due to the fact that the requested test voltages are often quite high compared to the real application. Based on the experience of ZVEI member capacitor manufacturers, PD levels vary with time, test setup and additional boundary conditions such as temperature, pressure, humidity, and mechanical stress (i.e. during transport).

Customers often argue, that the requested partial discharge limits (voltage and apparent charge level) are essential parameters to prove the reliability and safety of the product and insulation system. Often, system PD requirements are translated to the system components like the capacitors. However, there are no test results, theories or other evidence which correlate the measured PD- and/or voltage-level to capacitor lifetime. This is corroborated by ZVEI member experience, where insulation failures in Power Electronic Capacitors have been found to be a seldom and completely random occurrence with no correlation to PD measurements. Customer specified PD tests on the insulation system are recommended for new components and new insulation materials, however good PD results do not assure the reliability of the terminal to case insulation.

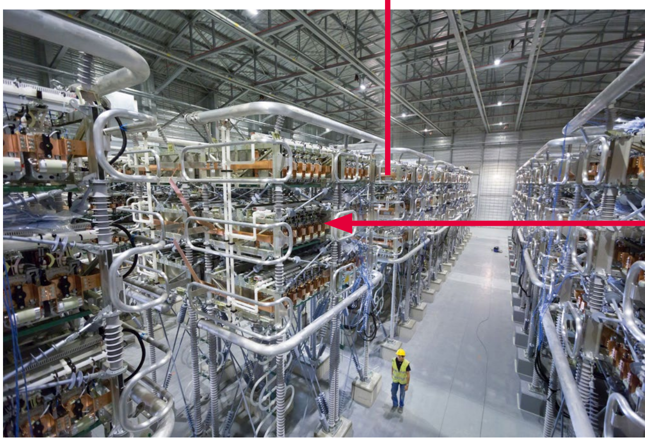
Furthermore, efforts to reach low PD levels at high voltages lead to design changes, which negatively impact other capacitor properties. For example, in order to reduce PD levels or increase PD voltages, thicker insulation is often used to reduce the electrical field strength. Thicker insulation increases the thermal resistance and therefore the internal temperature of the capacitor, which has been proven to have a negative impact on lifetime. Impact on size and weight as well should be taken into consideration.

Power Electronic Capacitor manufacturers who are members of the ZVEI therefore recommend basing PD requirements on the actual voltages present in the application. In addition to the voltage level, the waveform should also be considered (AC, DC + AC, etc.).

Currently, all DC Power Electronic Capacitors are commonly tested with pure AC and according to the demands of the customer. The required PD test voltage value and voltage form (pure AC) is not likely to be encountered during normal operation of the capacitor. This is particularly the case for the large DC storage capacitors which are used in VSC* converters of HVDC transmission systems.

* Voltage Source Converter

Source: Siemens AG



Source: Siemens AG
Typical Voltage Source Converter Installation

Source: ELECTRONICON Kondensatoren GmbH/
Multiple Caps per tower, depending on the design of the VSC converter

6 Proposal for partial discharge test for DC Power Electronic Capacitors

Typically, a measurement according to the procedure given in IEC 60270 [4], Section 8.3.2.2 is specified by most customers.

It is defined by two different parts, T_1 and T_2. During the first part a higher voltage U_1 than the voltage used for measurement U_2 is applied in order to trigger the start of partial discharges. The measurement reading is then taken at the end of the time frame T_2 for 5 seconds.

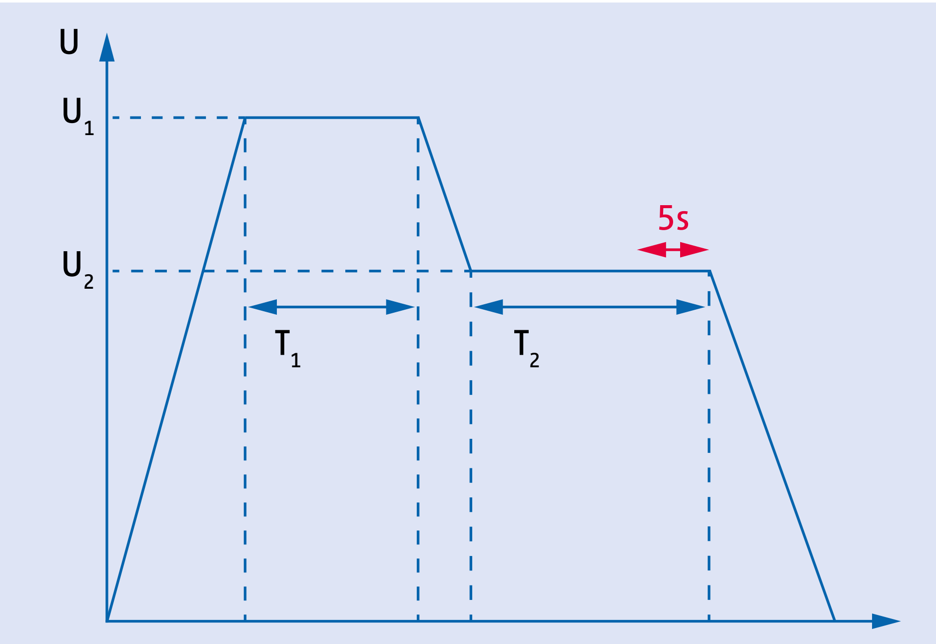


Figure 1: Measurement procedure according to IEC 60270, clause 8.3.2.2
Measurement with pre-stressing

The times T_1 and T_2 are normally in the range of 10...60 s. T_1 = 60 s and T_2 = 30 s can be used as a reference for type testing. T_1 can be reduced, but it is then recommended to increase U_1 in order to ensure the activation of the partial discharge during the first part of the test.

$$\gamma = \frac{U_1}{U_2} \quad \text{is typically in the range of 1.2 to 2.0}$$

In order to establish a more typical and representative test, a combined DC and AC voltage is recommended for all PD tests on DC capacitors:

$$U_{PD} = U_{DC_{test}} + U_{AC_{test}}$$

Where the U_{PD} test voltage will have the same peak value as the pure AC test voltage.

This paper proposes a formula to calculate the PD test voltage for Power Electronic Capacitors dependent on the nominal voltage U_N of the capacitor.

$$U_{PD_{DC}} = \alpha \cdot \beta \cdot U_{NDC}$$
$$u_{PD_{AC}}(t) = \alpha \cdot (1-\beta) \cdot U_{NDC} \cdot sin(\omega t)$$

$$\begin{aligned} u_{PD_{DC+AC}}(t) &= U_{PD_{DC}} + u_{PD_{AC}}(t) \\ &= \alpha \cdot U_{NDC} \cdot \big(\beta + (1-\beta) \cdot sin(\omega t)\big) \end{aligned}$$

With:

U_{NDC}	rated DC voltage of capacitor according IEC 61071
α	„overvoltage factor“
β	„DC factor“
$U_{PD_{DC}}$	PD test voltage, DC part
$u_{PD_{AC}}(t)$	PD test voltage, AC part
$u_{PD_{DC+AC}}(t)$	Superimposed test voltage

Varying α and β leads to different voltage forms:

1. Setting $\alpha = 1$ and $\beta = 1$ leads to a pure DC voltage: $u_{PD_{DC+AC}} = U_{NDC}$
2. Setting $\alpha = 1$ and $\beta = 0$ leads to a pure AC voltage: $u_{PD_{DC+AC}} = U_{NDC} \cdot sin(\omega t)$ and therefore to a AC voltage with a peak value of the rated DC voltage.

Then, to convert the usual $u_{PD_{AC}}$ requirement into a $u_{PD_{DC+AC}}$ with the same peak value the overvoltage factor should be calculated as follows

$$\alpha = \frac{u_{PD_{AC}} \cdot \sqrt{2}}{U_{NDC}}$$

β can be agreed between customer and capacitor manufacturer. Reference values can vary between 0.55 and 0.75.

As the test has two parts with different test voltages, either only the DC-part or the AC-part or both voltages can be changed. This happens when the voltage is ramped up to U_1 as well as the moment when the voltage is changed from U_1 to U_2.

Practically, it makes sense to only adjust one of the two voltage sources. Since varying the DC source is typically more difficult than variation of the AC source, it is recommended to keep the DC voltage constant during the test.

Source: Schleich GmbH

7 Example of test parameters for partial discharge tests on Power Electronic Capacitors

Typical AC PD-testing voltage levels for U_1 and U_2 for a nominal capacitor voltage of U_N = 2.8 kV_{DC} have been U_1 = 5.0 kV_{ACrms} and U_2 = 3.0 kV_{ACrms}.

In this case the overvoltage factor during the timeframe of T_2 (as shown in Fig.1) is

$$\alpha = \frac{3000 \cdot \sqrt{2}}{2800}$$

$$\alpha \approx 1.5$$

If the DC voltage should be kept constant during the measurement $\alpha \cdot \beta$ has to stay constant as well ($\alpha_1 \cdot \beta_1 = \alpha_2 \cdot \beta_2 =$ constant).

If we also want to keep the ratio $\gamma = \frac{U_1}{U_2} = 1.66$ for the superimposed PD test voltage we have to set

$$\begin{aligned}
U_1 &= \gamma \cdot U_2 \\
u_{PD_{DC+AC}1}(t) &= \gamma \cdot u_{PD_{DC+AC}2}(t) \\
\alpha_1 \cdot U_{NDC} \cdot \big(\beta_1 + (1-\beta_1) \cdot sin\,(\omega t)\big) &= \gamma \cdot \alpha_2 \cdot U_{NDC} \cdot \big(\beta_2 + (1-\beta_2) \cdot sin\,(\omega t)\big) \\
\alpha_1 \cdot \big(\beta_1 + (1-\beta_1) \cdot sin\,(\omega t)\big) &= \gamma \cdot \alpha_2 \cdot \big(\beta_2 + (1-\beta_2) \cdot sin\,(\omega t)\big) \\
\alpha_1 \cdot \beta_1 + \big(\alpha_1 - \alpha_1 \cdot \beta_1\big) \cdot sin\,(\omega t) &= \gamma \cdot \big(\alpha_2 \cdot \beta_2 + \big(\alpha_2 - \alpha_2 \cdot \beta_2\big) \cdot sin\,(\omega t)\big) \\
\tau + \big(\alpha_1 - \tau\big) \cdot sin\,(\omega t) &= \gamma \cdot \big(\tau + \big(\alpha_2 - \tau\big) \cdot sin\,(\omega t)\big)
\end{aligned}$$

$$\Rightarrow \alpha_1 = \gamma \cdot \alpha_2$$

$$\Rightarrow \beta_1 = \frac{\alpha_2}{\alpha_1} \cdot \beta_2 = \frac{\beta_2}{\gamma}$$

We now have a full set of parameters for a complete measurement procedure:

$$\alpha_2 = 1.5$$
$$\alpha_1 = \gamma \cdot \alpha_2 = 1.66 \cdot 1.5 \approx 2.5$$
$$\beta_2 = 0.55$$
$$\beta_1 = \frac{0.55}{1.66} = 0.33$$

resulting in the following voltage forms for the superimposed PD test:

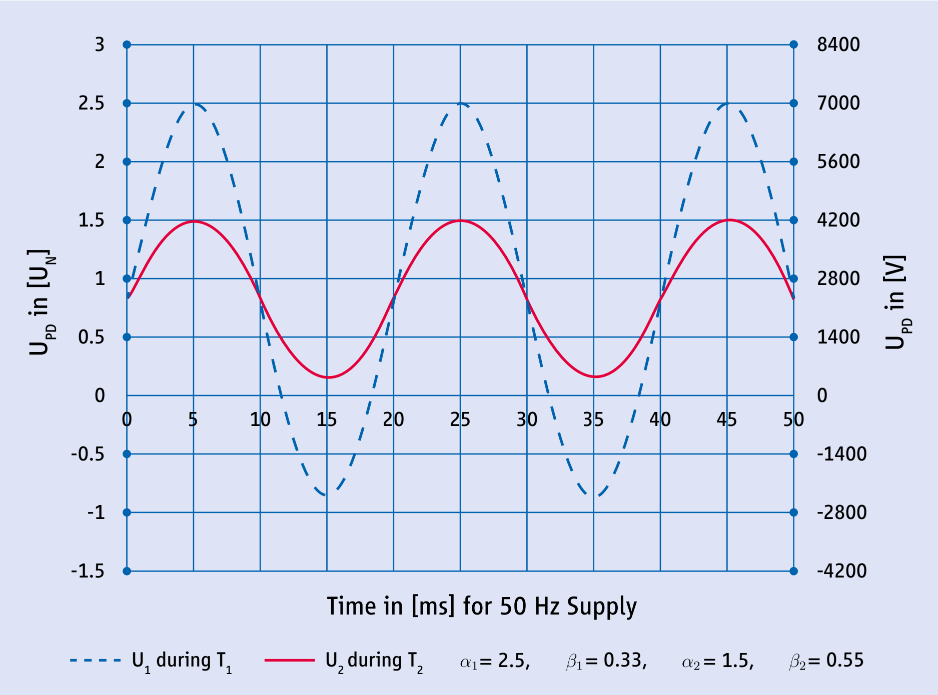


Figure 2: PD Test voltages

To sum up, the proposal for this specific example will be as follows:

- Set α_2 and β_2 (preferably $\alpha_2 = 1.5$ and $\beta_2 = 0.55$)
- Calculate γ from customer specification for PD measurement $\frac{U_1}{U_2}$
- Switch on the DC-source and set the voltage to $U_{PD_{DC}} = \alpha_1 \cdot \beta_1 \cdot U_{NDC}$
- Switch on the AC-source and rise voltage to

$$u_{PD_{AC}1}(t) = \alpha_1 \cdot (1 - \beta_1) \cdot U_{NDC} \cdot sin(\omega t)$$

- Keep the voltage level for $T_1 = 60\,\mathrm{s}$
- Lower the AC-voltage to

$$u_{PD_{AC}2}(t) = \alpha_2 \cdot (1 - \beta_2) \cdot U_{NDC} \cdot sin(\omega t)$$

- Keep the voltage level for $T_2 = 30\,\mathrm{s}$
- Take the PD reading.
- Lower the AC and DC voltage to $0\,\mathrm{V}$ and switch off both voltage sources.

8 Final recommendations and Conclusions

Statements regarding the lifetime of capacitors based on PD measurement results are not possible. Therefore partial discharge measurements parameters (voltage levels, waveforms and acceptance criteria) as part of routine or type tests for Power Electronic Capacitors should be agreed between customer and capacitors manufacturers independently.

An agreement is highly recommended in order to avoid overly complex designs which may not be technically necessary and could result in higher complexity and consumption of resources.

A combined DC + AC test voltage is presented as a more practical approach for the typical application of DC Power Electronic Capacitors.

If partial discharge measurements are intended to be repeated by the customer, either as routine or type test, the test setup and conditions should meet the requirements of the IEC standards referred to in this guide. Based on the experience of ZVEI member capacitor manufacturers, PD levels vary with time, test setup, and additional boundary conditions such as temperature, pressure, humidity, and mechanical stress (i.e. during transport). Consequently, the repeatability of such measurements is limited. Performing PD measurements and interpreting the test results requires extensive knowledge of PD test technology.

9 Literature

[1] IEC 61287-1:2014
Railway applications - Power converters installed on board rolling stock - Part 1: Characteristics and test methods

[2] IEC 61800-5-1:2007+AMD1:2016 CSV (Consolidated Version)
Adjustable speed electrical power drive systems - Part 5-1: Safety requirements - Electrical, thermal and energy

[3] Partial discharge measurement and diagnostics for applications in the low voltage range ≤ 1,000 Volt, ZVEI - Division Electrical Winding and Insulation Systems, June 2016

[4] IEC 60270:2000+AMD1:2015, “High Voltage Test Techniques - Partial discharge measurements”, 2015

Die Elektroindustrie

ZVEI e. V.
Lyoner Straße 9
60528 Frankfurt am Main

Phone: +49 69 6302-0
Fax: +49 69 6302-317
E-Mail: zvei@zvei.org
www.zvei.org