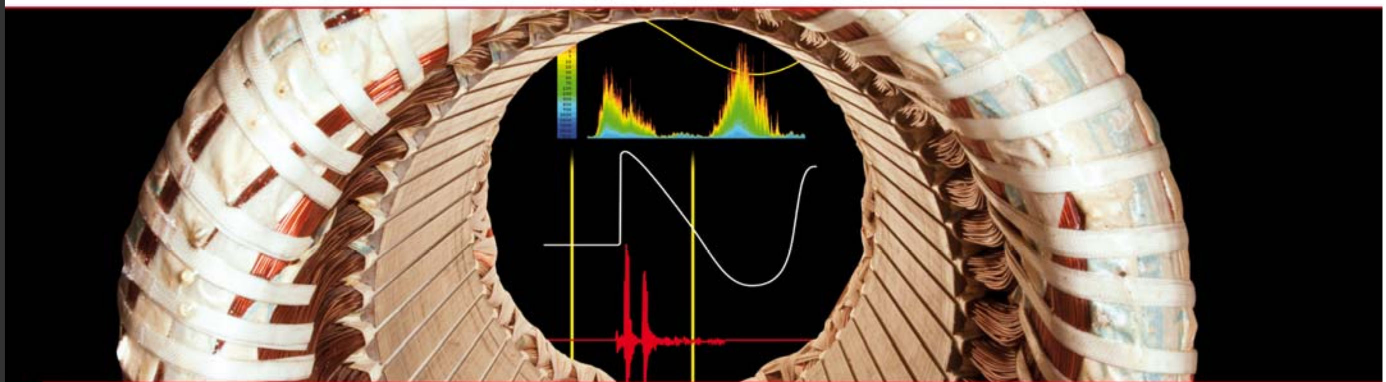
Innovative Test & Measurement Technology
For the maintenance, repair and production of motors and generators

SCHLEICH
Advanced Test Technologies



Perfect Test Technology of Watts to Megawatts

Partial discharge test to evaluate windings of low-voltage electric motors with regard to frequency converter capability as well as general insulation strength

> Introduction

Within recent years the importance of the partial discharge test to evaluate insulations in electric motors has increased. This is especially true due to the large increase of Variable Frequency Drives (VFD's) for motor control. Many motor professionals speak of partial discharge testing but only a few completely understand what partial discharge is.

This article is meant to provide a general description of partial discharge (PD) testing.

> What is a partial discharge?

The example in Figure 1 illustrates a typical breakdown from conventional high-voltage testing with alternating voltage.

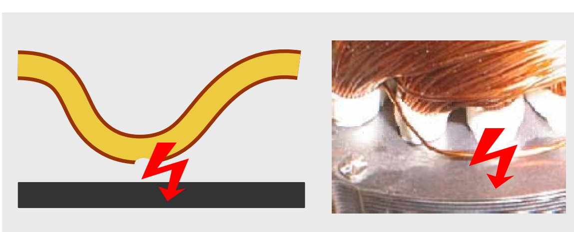


Figure 1 | Damaged lead close to the laminations

With motor testing the evaluation usually states – the motor must not have any breakdown, or excessive leakage current; however, the determination of *how much is too much current during the high-voltage test* is not that simple.

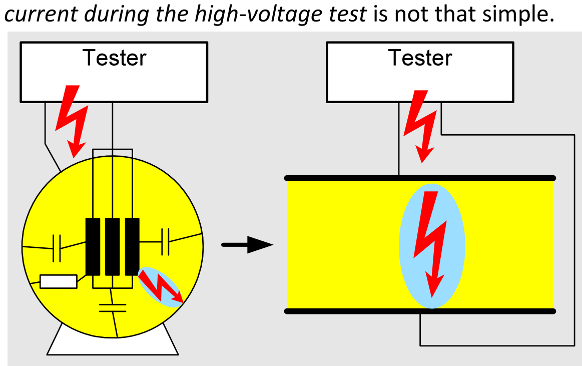


Figure 2 | Breakdown or capacitive leakage current

In a manufacturing environment, the maximum allowable high-voltage current can be determined by means of comparative measurements. However; for repair facilities that normally do not have this current limit value this can be an issue. Depending on the insulation's capacity in the motor, the current is low in smaller electric motors and higher in larger motors. The experienced engineer or technician often feel that too high of leakage current might flow in the motor if he hears crackling noises during the high-voltage tests. This example, while not depicting a complete breakdown, does show the effects of partial discharge. Our task is measuring and evaluating these effects on motor reliability.

In relation to the word partial, the breakdown only occurs in specific locations of the insulation. This is where the partial discharge occurs. This location has a partial insulation weakness or a defect from manufacturing of the stator winding of the electric motor or generator.

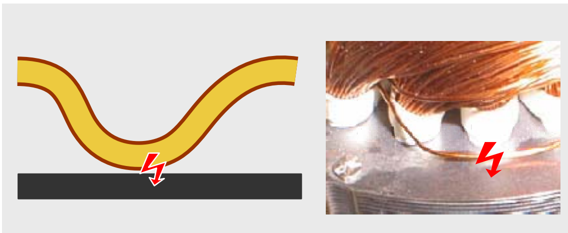


Figure 3 | Partial discharge in a small air gap

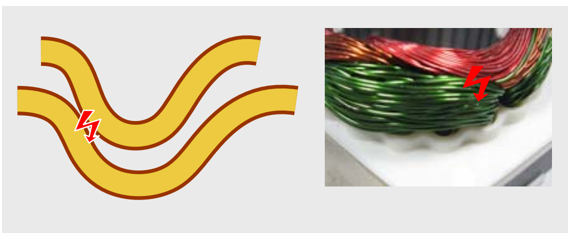


Figure 4 | Partial discharge between windings with direct contact

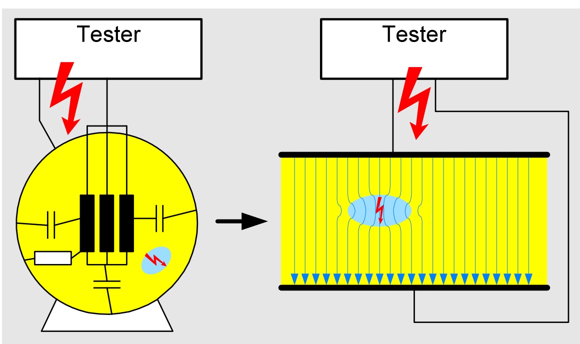


Figure 5 | Partial discharge in a strongly stressed or area of insulation

This weak spot is excessively stressed during the operation of the electric motor or during high-voltage testing. This weak spot cannot withstand this increased stress. As a result there is a partial breakdown in this location. This partial breakdown is referred to as partial discharge. However, the remaining insulation can still withstand the increased voltage stress so that there is not a complete breakdown.

Figure 6 illustrates the principal insulation setup. The high-voltage is connected between two electric leads (e.g. winding and laminations or lead and lead).

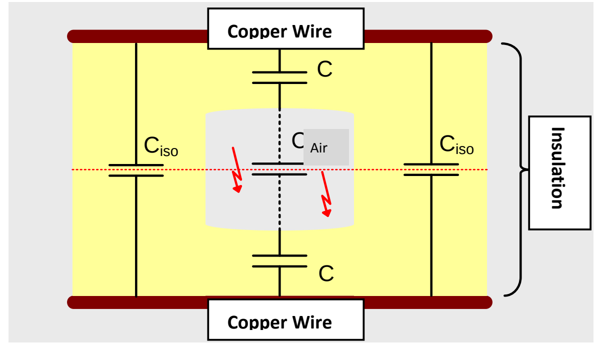


Figure 6 | Partial discharge illustrated by means of an equivalent circuit

The electric leads are separated from each other by the insulation. In a perfect homogeneous world the insulation can be understood like at a large condenser (C_{IR}). But due to a defect in the insulation there can be locations or areas that are overcharged locally by a high electric strength (C_{air}). This is illustrated in the middle part of the graphic. A partial discharge occurs in this overcharged location or area.

The consequence of this partial discharge is a slow but continuous weakening of the insulation system. Based on the concept of *constantly dripping of water wearing away a rock,* the partial discharges will lead to total erosion of a defective location. This will lead to a catastrophic failure of the electric motor. So the goal should always be not have any partial discharge in electric motors or generators.

Partial discharge is a voltage-dependent physical effect. Eventually with increasing operating voltage and motor class partial discharge will occur. The one question must be answered is what test voltage level should be used to adequately check for partial discharge? The answer is in the application of the electric motor. If unknown, one might choose the most rigorous applications – that of a VFD system.

> Electric motors in industrial plants without VFD's

An electric motor that is directly connected to the MCC without a VFD is only charged with the main AC voltage. It sees only voltage peaks resulting in switching the motor on and off. As a result, testing this application for partial discharge is unnecessary.

> High-voltage machines

High-voltage motors (usually those above 5kV operating voltage) require a higher corresponding test voltage to check whether it is free from partial discharges. These higher operating voltages require special high-voltage AC insulation systems.

> Electric motors in industrial plants with VFD's

Electric motors that are operated with VFD's also should be tested with a higher test voltage to check whether they have partial discharge. Several questions are often asked. *Why* should a motor with a VFD be tested with an increased test voltage - and- *How can high voltage even occur at an electric motor operated by a VFD?* The answer is found in the basic functioning principle of the frequency converter. A VFD supplies three-phase AC voltage to an electric motor that is first rectified and evenly stored in correspondingly large capacities. The loading or reservoir capacity within the frequency converter is known as the continuous current intermediate circuit. The theoretical maximum continuous current level in this circuit results from the effective value of the main input voltage multiplied by the square root of 2 (√2). The level of the direct voltage is the peak value of the main supply's effective value.

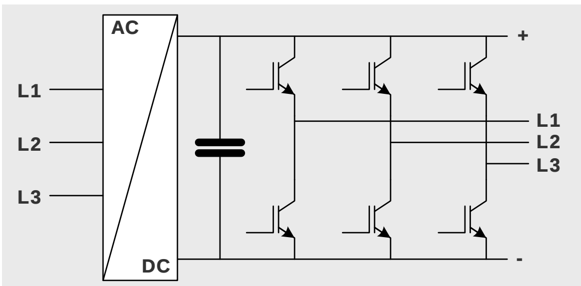


Figure 7 | Principle wiring of the frequency converter

The stored direct voltage is again converted to alternating voltage by modern electronic switching devices. The result is a non-uniform sine wave synthesizing a signal combination of rectangular pulses. The amplitude of the rectangular signal cannot be modified as the electronic switches either switch the direct voltage to the electric motor or not. However, the frequency converter can vary the pulse duration (switch-on duration of the electronic switches). By varying the pulse width the sine wave is quasi simulated. This procedure is called pulse width modulation.

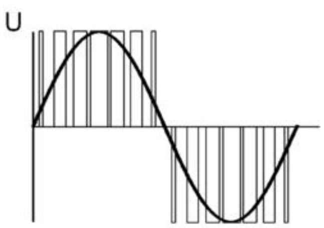


Figure 8 | Sinus signal simulated by rectangular pulses

In recent years, the almost rectangular pulses have seen a faster rise time. This is in an attempt by the electronic switches' semiconductor manufacturers to keep the power loss from the switch as low as possible during the switchover cycle. The reason is that the considerable losses (i.e. the warming-up of the semiconductors) always occur during the switchover cycle. This means the faster the electronic switch switches, the lower the losses and the lower the cooling expenditure in a frequency converter.

But from the electric motor manufacturers' view fast rise times represent an issue. The reason is that fast rise times lead to voltage peaks during the switchover cycle [1].

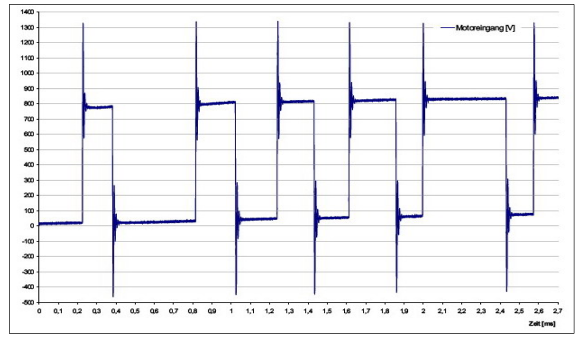


Figure 9 | Rectangular signals with a rise time and overvoltage peaks

This is due to the rectangular signals only existing based on combined sinus signals of various frequencies and various amplitudes in the electrical design. The higher a rectangular edge is the higher the frequencies are in the sinus signals simulating the edge. The amplitude of the sinus signals also steadily increase. The voltage peaks become even higher when the electric motor is connected via a long cable.

When signals are switched very quickly into an inductance (i.e. the electric motor winding) the motor winding impedance acts as a low pass filter. The high frequencies are non-linearly impressed across the end turns or phase ends. This results in voltage "piling up" against the motor terminals due to the impedance mismatch. The net effect is that voltage drops are excessive in certain physical locations within the motor winding.

Figure 10 shows the connection between a fast rise time and the resulting voltage drop over the winding of a cycle.

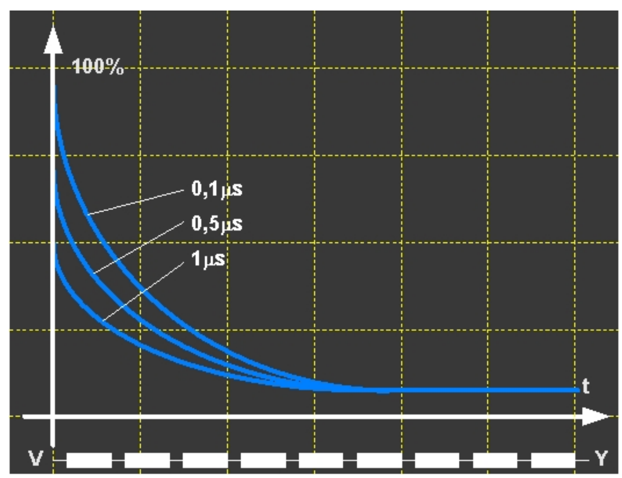


Figure | Voltage cycle over the winding depending on the rise time

There is a paper regarding the level of the overvoltage pulse [10]. A connection has been determined between the overvoltage pulse and the rise time. The occurring overvoltage was determined to be a factor. This factor must be multiplied with the intermediate circuit voltage U_{DC} to determine the absolute value of the overvoltage. Depending on the rise time four stress ranges are defined for the machine.

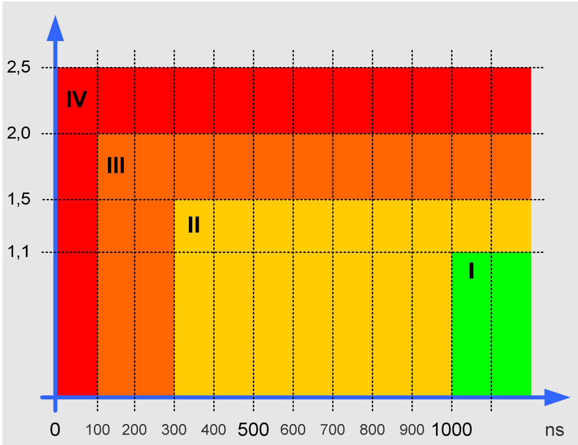


Figure 11 | Stress range I – IV with overvoltage factor depending on the rise time

> Test methods: Current pulse or high-frequency measurement?

As mentioned earlier partial discharge occurs at weak insulation spots when the charge in the weak spot becomes too high. As the leakage current does not increase measurably at a discharge site, so the question is asked: *"How can partial discharge be measured?"*

The answer is in the definition of partial discharge. When there is a discharge and voltage is still connected to the test object the object is immediately recharged again. With this the partial discharge can be directly measured via the charge. The charging pulse has a width of only a few nanoseconds and has a very fast high-frequency current pulse. Therefore the measuring technique has to be able to detect this fast pulse.

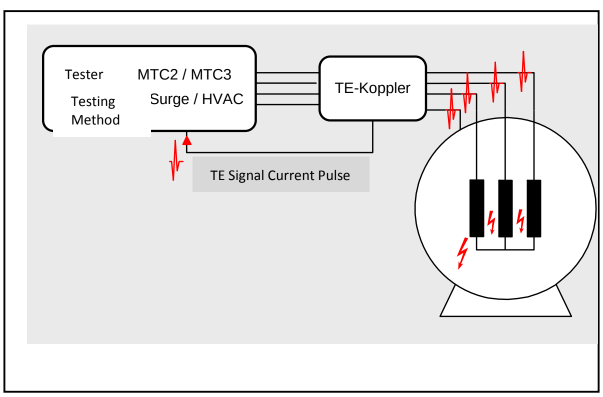


Figure 12 | Partial discharge test at a motor/alternator or stator with capacitor for the high-frequent current pulse

The PD-capacitor is either integrated in the tester or is integrated into the test leads to the test object.

Parallel to the discharge there is also an electro-magnetic emission of the discharge signal. This is similar to an electric spark or discharge. This is defined by radio operators, radio units (RF), which are based on this discharge and the connected electro-magnetic wave. The spark generates a very high-frequency broadband signal which can be identified by a multi-band radio.

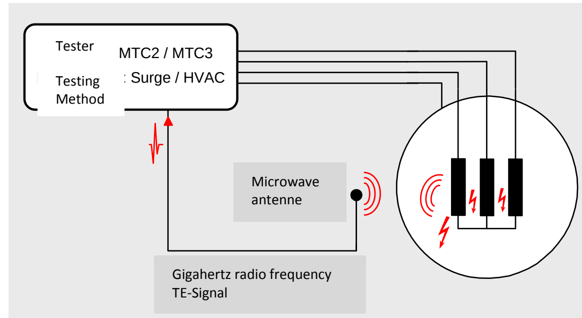


Figure 13 | Partial discharge test at a stator with antenna for the high-frequent current pulse

SCHLEICH of Hemer Germany has developed and has been using current pulse as well as the high-frequency antenna measurement for years. Both methods procedures have advantages and disadvantages. The current pulse measurement method has a disadvantage that it sometimes is impacted by external perturbations. Thus this can lead to a false positive at the electric motor. There may be a misinterpretation of actual measured partial discharge. This disadvantage can be effectively reduced by special filters but it cannot be completely eliminated.

Unlike the pulse current pulse method the high-frequency antenna technique has one main advantage. Depending on the selected high frequency range there are no external perturbations or their effects are greatly reduced. Measuring in areas near radio stations, radio units or mobile phones cause problems; however, the greatest disadvantage to this technique is that a completely sealed motor does not let high-frequency signals outside of the motor enclosure. These enclosures are like a Faraday cage for the winding inside.

Due to these issues the best results can be derived from using both techniques depending upon the application.

> Online or off-line measurements?

Distinguishing between the two operating conditions of an electric motor, with online measurement the motor is in operation and with the off-line measurement, the motor is turned "off".

The partial discharge equipment manufactured by SCHLEICH currently operates the partial discharge test as an off-line measurement. In the off-line mode the machine can be measured during the winding repair or when the motor is shut down for maintenance purposes. The disadvantage of the off-line operation is that some insulation problems that arise during operation from centrifugal and magnetic forces cannot be measured. The main advantage of the off-line measurement is the easy interpretability of partial discharge effects. These effects are not superimposed or influenced by disruptions in the operation of a VFD.

> High-voltage or surge test as precondition for the partial discharge test

The partial discharge test can be performed in combination with a high-voltage test or a surge test. Both test methods serve as a basic test in order to activate the partial discharge.

The high-voltage test with alternating voltage measures the dielectric strength and in addition the partial discharge between the windings and/or the windings to the body.

The surge test looks directly at the winding (winding to winding) to detect weak insulation. It also measures the partial discharge.

However under certain conditions the partial discharge test in combination with the surge test does not react to sensitive weak spots between the winding and the body or between the cycles. Both test methods are recommended to measure a partial discharge for machine for reliably.

> The physical unit pC (pico Coulomb)

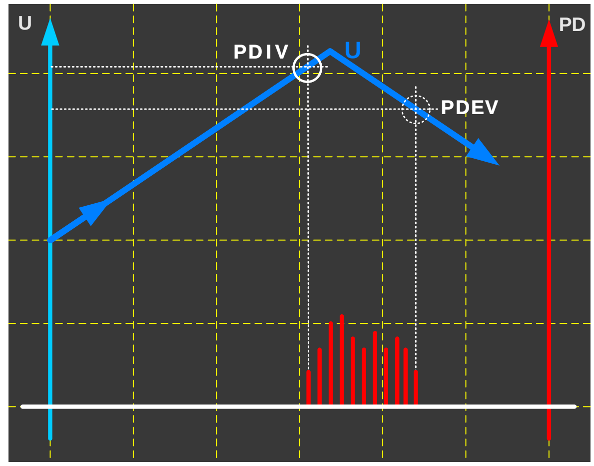
The unit for the charge or discharge is pC. The equation of the charge is: Q = C * U. Thus the charge is the product of the capacity (it stores the charge) and the connected voltage level.

The partial discharge is measured in the range of approx. 1pC up to several 1000pC. 1pC is very low. The voltage from 1V to a capacity of 1picoFarad results in a picoCoulomb charge!

In practice it is not mandatory to use testers with a picoCoulomb-display. It is sufficient to detect via a sensitive measuring technique whether there is a partial discharge or not. In doing so the determination of the partial discharge inception and extinction voltages are more important than the absolute measuring value of the partial discharge in the unit picoCoulombs.

> Inception and extinction voltages

For the insulation's evaluation the inception and extinction voltages are often measured. Hereby the high-voltage (no matter if alternating high-voltage or surge voltage) is increased continuously from a start value up to a maximum value. As soon as the partial discharge starts at a specific voltage, this is defined as partial discharge inception voltage (PDIV). Afterwards the high-voltage is reduced until the partial discharge disappears. This value is the partial discharge extinction voltage (PDEV).



Picture 14 | Partial discharge inception and partial discharge extinction voltage

A quality insulating system is characterized by the fact that both voltage values are on a high level. Basically you can say: “The higher the better.” The voltage values should be at least higher than the level of the voltage peaks that could occur during the operation. For this the standards predefine average standard values.

> Conclusions

Based on our long-term and varied experience with numerous motor manufacturers worldwide we can speak very positively of the partial discharge test. It is a test method that covers manufacturing faults as well as aging effects in a unique way. Therefore this test method is of great importance for the production as well as for repair and maintenances facilities. Our know-how goes from 100 Horsepower to 4MW motors and alternators respectively.

The measurement of the current pulse in the supply leads to the electric motor has turned out to be very positive as alternative to the high-frequency measurement (with antenna) at electro-magnetic encapsulated motors. The current pulse measurement also allows performing partial discharge tests reliably at assembled electric motors. The operator does not have to think about the ideal positioning of the antenna.

In addition SCHLEICH covers the partial discharge test with an internationally recognized combination based on the alternating high-voltage and surge voltage. The switchover between the various winding connections at the electric motor is performed fully automatically. This is done at test voltages as high as 50KV.

All SCHLEICH testers are developed and manufactured in-house, we do not subcontract any part of our test equipment to other sources. With over 25 years of experience in testing and manufacturing of high quality test equipment. All of our testers are “Made in Germany” at our facility in Hemer.

Authors:
Dipl.-Ing. Jan-Philipp Lahrmann
Dipl.-Ing. Martin Lahrmann
February 2012

SCHLEICH GmbH
An der Schleuse 11
D-58675 Hemer
Phone: +49 2372 94980
Email: welcome@schleich.com
Internet: www.schleich.com

> References

Some information was taken from the following references:

[1] Paper No. PCIC-2004-27: „PARTIAL DISCHARGE INCEPTION TESTING ON LOW VOLTAGE MOTORS“; IEEE; 2004

[2] IEC/TS 60034-18-41 ed1.0: „Rotating electrical machines - Part 18-41: Qualification and type tests for Type I electrical insulation systems used in rotating electrical machines fed from voltage converters”; 2006

[3] IEC/TS 60034-18-42 ed1.0: Rotating electrical machines - Part 18-42: Qualification and acceptance tests for partial discharge resistant electrical insulation systems (Type II) used in rotating electrical machines fed from voltage converters”; 2008

[4] IEC/TS 60034-27: Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines”; 2006

[5] IEC/TS 61934 ed2.0: „Electrical insulating materials and systems - Electrical measurement of partial discharges (PD) under short rise time and repetitive voltage impulses”; 2011

[6] VDE 530-18-41: „Drehende elektrische Maschinen Teil 18-41: Qualifizierung und Qualitätsprüfungen für teilentladungsfreie elektrische Isoliersysteme (Typ I) in drehenden elektrischen Maschinen, die von Spannungsumrichtern gespeist werden“; 2011

[7] VDE 530-18-42: „Drehende elektrische Maschinen Teil 18-42: Qualifizierungs- und Abnahmeprüfungen teilentladungsresistenter Isoliersysteme (Typ II) von drehenden elektrischen Maschinen, die von Spannungsumrichtern gespeist werden“; 2011

[8] VDE 530-27: „Drehende elektrische Maschinen Teil 27: Off-Line Teilentladungsmessungen an der Statorwicklungsisolation drehender elektrischer Maschinen“; 2011

[9] R.H.Rehder - W.J.Jackson – B.J.Moore; Designing Refiner Motors to Withstand Switching Voltage Transients

[10] M.Tozzi – A. Cavallani – G.C. Montanari; Monitoring Off-Line and On-Line PD Under Impulsive Voltage on Induction Motors – Part 1: Standard Procedure”; 2010

[11] M.Tozzi – A. Cavallani – G.C. Montanari; Monitoring Off-line and On-line PD Under Impulsive Voltage on Induction Motors – Part 2: Testing”; 2010