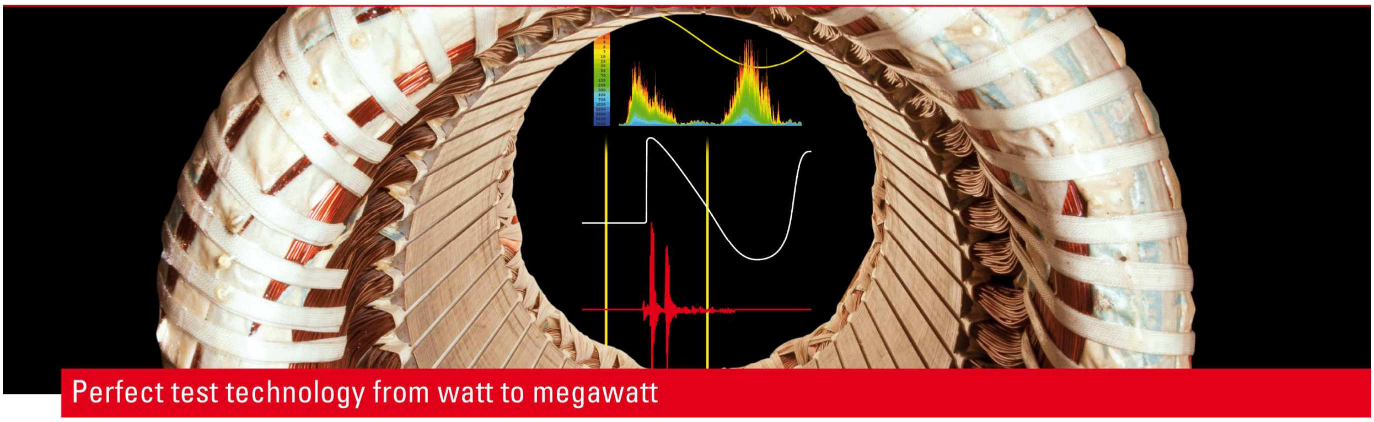


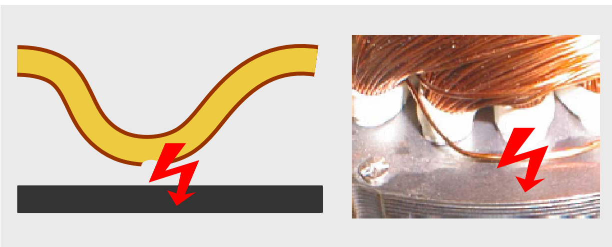
Partial discharge test to evaluate windings of low-voltage electric motors with regard to frequency converter capability as well as general insulation strength

> Introduction

The partial discharge test has become more important to evaluate insulations in electric motors within the last few years. This is especially true do to the large increase of VFD's for the motor control. Our experience shows that many operators speak of the partial discharge test but only a few really understand what partial discharge means in depth.
This article is to "shed light" on this type of testing. This is not a scientific paper but a general description of the test method and its applications.

> What is a partial discharge?

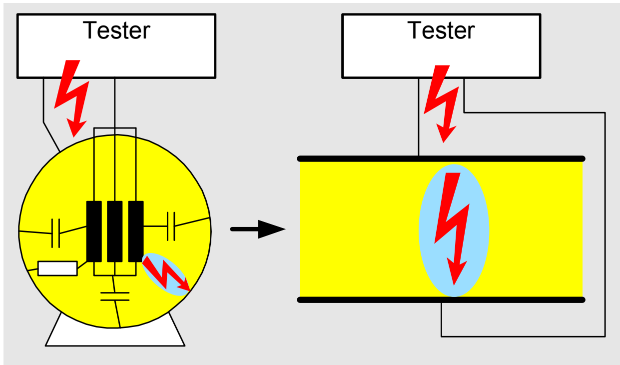
The example below illustrates a typical "complete breakdown" from the conventional high-voltage test with alternating voltage.



Picture 1 | Damaged lead close to the laminations

Electric motors are usually evaluated as follows: "The motor must not have any breakdown, or excessive leakage current."

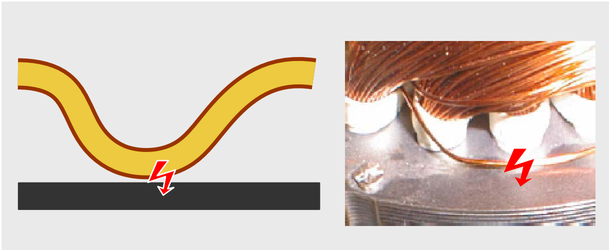
The evaluation of "*How much is too much current at the high-voltage test*" is not that simple, to start with.



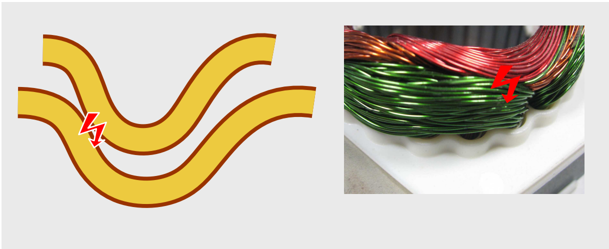
Picture 2 | Breakdown or capacitive leakage current

The maximum allowable high-voltage current can be determined and indicated by means of comparative measurements in a manufacturing environment. However for repair facilities and technicians that normally do not have this current limit value this is an issue. Depending on the insulation's capacity in the motor the current is low in smaller electric motors and correspondingly higher in larger motors. The experienced engineer / technician often feels that too high of leakage current might flow in the motor and/or if he hears cracklings noises during the high-voltage tests. In such cases it is not a complete breakdown, but has the effects of partial discharge. Our task is now to measure and evaluate this effect on reliabilty.

In relation to the word "partial" the breakdown only occurs in specific locations of the insulation and a partial discharge occurs.

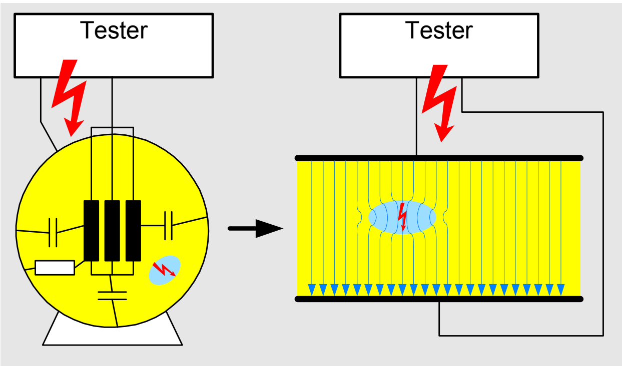


Picture 3 | Partial discharge in a small air gap



Picture 4 | Partial discharge between windings with direct contact

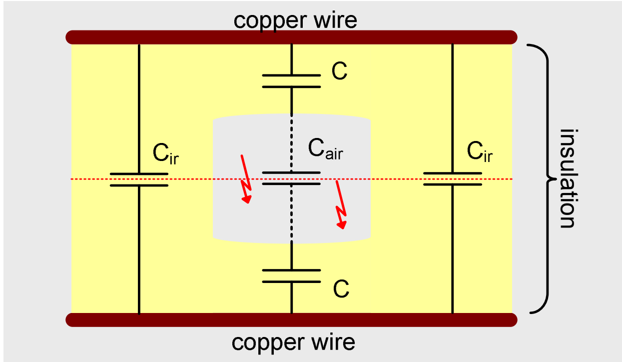
This location has a partial insulation weakness or a defect when manufacturing of the stator winding of the electric motor or generator.



Picture 5 | Partial discharge in a strongly stressed partition

This weak spot is excessively stressed during the operation of the electric motor or during the high-voltage test. This weak spot cannot resist 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 resist the increased voltage stress so that there is not a complete breakdown.

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



Picture 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 partitions 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 partition.

The consequence of this partial discharge is a slow but continuous destruction of the functional parts of the insulation system. Based on the concept *"Constant dripping of water will wear away at a rock"* the permanent partial discharges continuously will lead to an erosion of a defective location. This inevitably causes the weakening of insulation at the defective location so the functioning insulation is soon not able to resist the stress. This leads to a complete breakdown and thus to a complete destruction of the electric motor. So the goal should always be not to have any partial discharge in the electric motor or generator. It is often only a matter of time until low partial discharges destroy the complete motor and or generator.

Partial discharge is a voltage-dependent physical effect. With increasing voltage partial discharge will occur eventually. The only question is what test voltage level should be used? The answer is in the application of the electric motor. The test voltage to be selected for the partial discharge depends on the respective application of the motor. If unknown this it is obvious choice is to assume that the motor could and will be used on a VFD system.

> Electric motors in industrial plants without VFD's

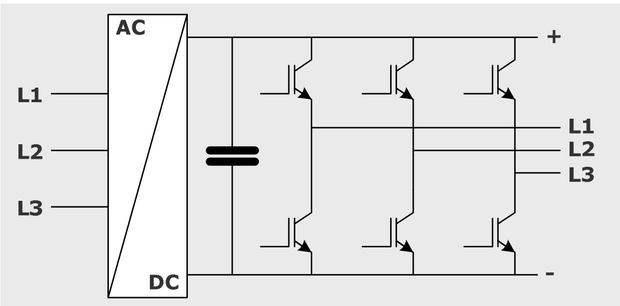
An electric motor that is directly connected to the MCC without VFD is only charged with the main AC voltage and only sees peaks resulting in switching the motor off and on, as a result it does not make any sense for this application to be tested at the motor with high test voltages to check whether it is free from partial discharges.

> High-voltage machines

High-voltage motors naturally require a test voltage that is correspondingly adapted to the high AC operating voltage to check whether it is free from partial discharges. Usually those motor above 5KV. The high operating voltage requires a special high-voltage AC insulation system. Taking this into consideration one must test at higher levels to insure proper test levels to meet the requirements.

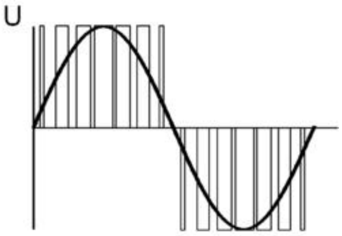
Electric motors in industrial plants with VFD’s

Electric motors that are operated with a VFD’s also have to be tested with an increased test voltage to check whether they are free from partial discharges. *Why* should a motor with a VFD be tested with an increased test voltage? The question many ask is? *How can high voltage even occur at an electric motor operated by a VFD?* The answer can be found in the basic functioning principle of the frequency converter. A VFD supplies three-phase AC voltage to and electric motor that is at first rectified and evenly and stored in correspondingly large capacities. The loading or reservoir capacity within the frequency converter is often indicated as continuous current intermediate circuit. The theoretically maximum continuous current level in the continuous current intermediate circuit results from the effective value of the main input voltage multiplied with √2. The level of the direct voltage is thus the peak value of the main supply’s effective value.



Picture 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 but a signal combination of rectangular pulses.



Picture 8 | Sinus signal simulated by rectangular pulses

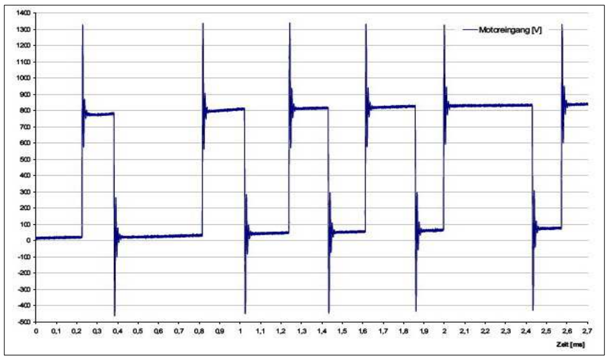
The amplitude of the rectangular signal cannot be modified as the electronic switches either switch the direct voltage to the electric motor or not.

However, the frequency converter can vary the pulse duration (switch-on duration of the electronic switches). By varying the pulse width the sinus is quasi simulated. This procedure is called pulse width modulation.

The almost rectangular pulses have an ever-increasing rise time within the last several years. This is in an attempt by the electronic switches’ semiconductor manufacturers to keep the power loss within 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 is in a frequency converter.

Thus the frequency converter manufacturer’s view high rise times as part of the goals in the development.

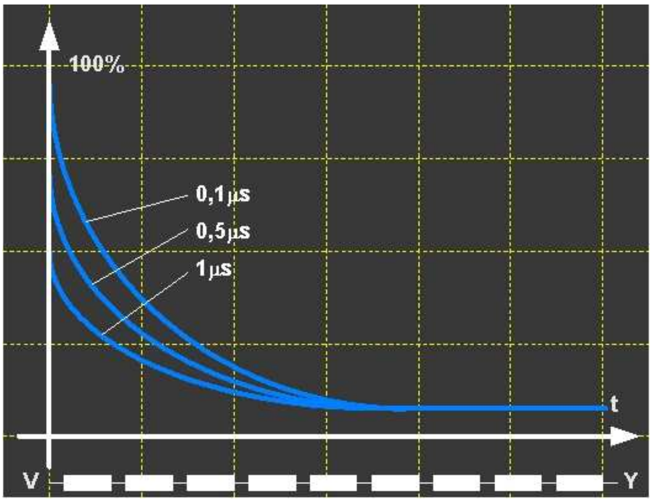
But from the electric motor manufacturers’ view high rise times represent a big problem. The reason is that high rise times lead to voltage peaks during the switchover cycle [1].


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

This is due to the fact that rectangular signals principally only exists 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 the sinus signals simulating the edge. The amplitude of the sinus signals also steadily increases. The voltage peaks become even higher when the electric motor is connected via a long cable.

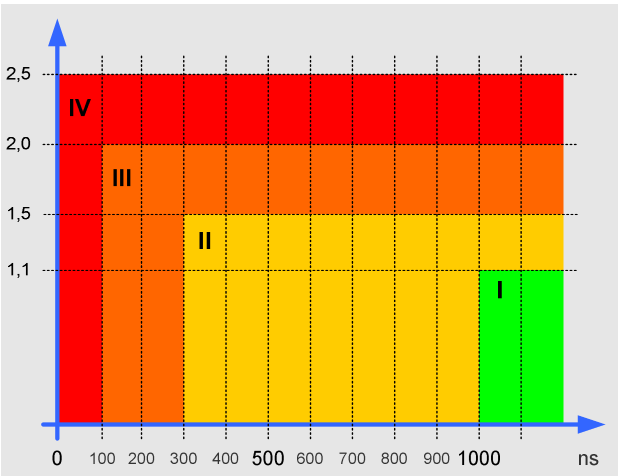
When the signals are now switched with a high rise time to an inductance (i.e. the electric motor) the high-frequencies of the rectangular signal are quasi filtered at the inductance. In the process high-frequencies signals drop sharply at the first few turn in winding of a coil at the terminal leads. Thus the turns of the winding at the beginning or close to the connection terminal are intensively charged by frequency converter operation.

The following graphic clearly shows the connection between a high rise time and the thus resulting voltage drop over the winding of a cycle.



Picture 10 | Voltage cycle over the winding depending on the rise time

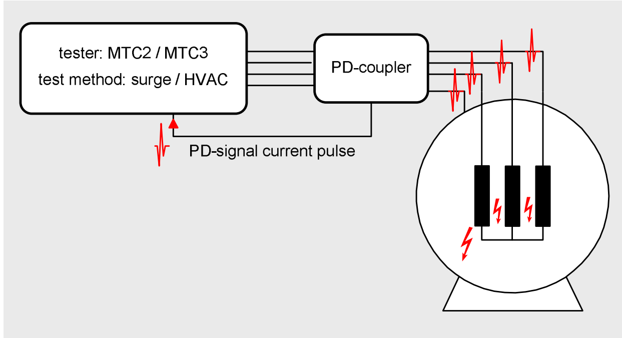
There is a very good paper regarding the level of the overvoltage pulse [10]. A connection between the overvoltage pulse and the rise time was determined here. The occurring overvoltage was determined as factor. This factor has to be multiplied with the intermediate circuit voltage U_{DC} to receive the absolute value of the overvoltage. Depending on the rise time 4 stress ranges of the machine were defined.



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

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

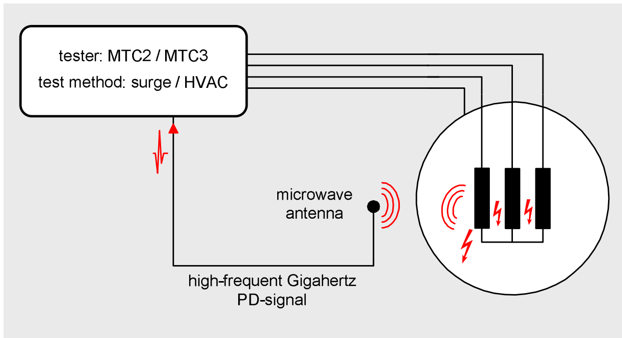
At the beginning we have already mentioned that partial discharge occurs at weak insulation spots when the charge in the weak spot becomes too high. As the leakage current does not increase measurably at an occurring discharge the question is asked: *"How can partial discharge be measured?"*
Principally the answer is in the definition of the partial discharge. When something is discharged and the voltage is still connected to the test object from the outside it is immediately recharged again. Thus the partial discharge can be directly measured via the charge. The charging pulse has a width of only a few nanoseconds. Thus it concerns a very fast high-frequent current pulse.
Therefore the measuring technique has to be able to detect this fast pulse.



Picture 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 comfortably stackable 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 spark and the connected electro-magnetic wave. The spark generates a very broadband high-frequency signal which could also principally be identified by a radio (multi-band radio).



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

SCHLEICH has already been using the current pulse as well as the high-frequent antenna measurement for many years. Both measurement procedures have advantages and disadvantages. You cannot say that one measurement procedure is fundamentally better than the other.
The procedure of the current pulse measurement has the disadvantage that it sometimes is impacted by external perturbations. Thus there is an apparent partial discharge at an electric motor but the measuring technique is misled by external disturbances. Hence there may be a misinterpretation of an apparently measured partial discharge. This disadvantage can be reduced to a high extent by special filters but it cannot be eliminated completely.

The high-frequency measurement of the electro-magnetic wave via a special antenna has the advantage that depending on the selected high frequency range there are no perturbations of external disturbances anymore or their effects are reduced. Logically you should not measure in areas where for example radio stations, radio units or mobile phones are operated. But the disadvantage of this measurement procedure is that a completely installed motor does not let any high-frequency signals get to the outside as the motor enclosure is like a Faraday cage for the winding inside.

Due to this we basically recommend both measurement procedures. Thus the best is always the combination of both measurements in order to use one of the two measurements depending on 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 there is no rotation.

SCHLEICH currently operates the partial discharge test as off-line measurement. In the off-line mode the machine can be measured during the repair of a winding or while the motor is shut down for maintenance purposes. The disadvantage of the off-line operation is that special insulation problems arising during the rotation due to the occurring centrifugal and magnetic forces which cannot be measured. The advantage of the off-line measurement is of course the easier interpretability of the partial discharge effects that are not superimposed or influenced by any disruptions e.g. in the operation of the VFD.

The off-line measurement is either performed in combination with the high-voltage test or surge test.

> 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 actually 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 primarily “looks “directly into the winding (from winding to winding) to detect weak insulation spots. In addition it also measures the partial discharge.

But under certain conditions the partial discharge in combination with the surge test does not react to sensitive weak spots between the winding and the body or between the cycles. Thus both test methods are recommended to measure a partial discharge on a machine for reliably. A combination of both procedures makes the most sense.

> 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.

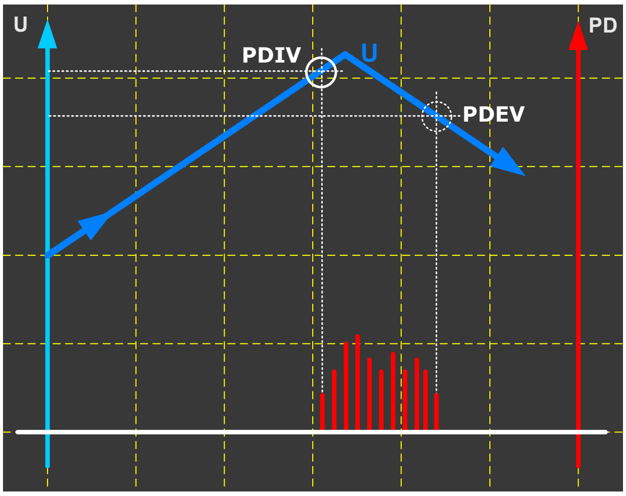
The partial discharge is measured in the range of approx. 1pC up to several 1000pC. 1pC is very, very low. The voltage from 1Volt to a capacity of 1picoFarad results in a Pico Coulomb charge!

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 Pico Coulomb.

Thus SCHLEICH manufactures partial discharge testers without using a Pico Coulomb display.

> 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).

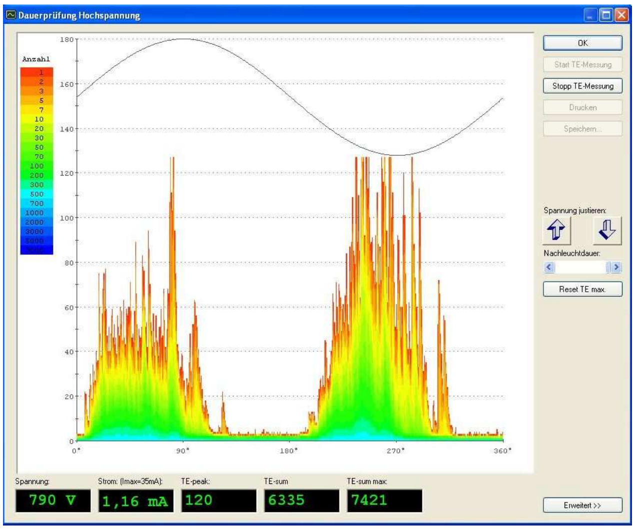


Picture 14 | Partial discharge inception and partial discharge extinction voltage

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.

> High-voltage testers with alternating high-voltage and partial discharge

This test technique has already been included in the SCHLEICH winding testers for the motor manufacturing for more than 10 years.



Picture 15 | Partial discharge at the high-voltage test with alternating voltage

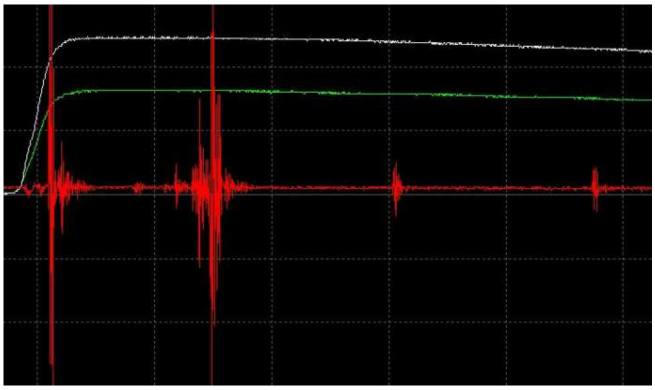
The testers MTC2 and MTC3 are characterized by the following typical features:

- partial discharge test according to national and international standards
- electronic sinus-high-voltage source
- adjustable high-voltage with very fine voltage resolution
- adjustable frequency of the high-voltage to be able to perform measurements for various application ranges and various markets
- capacitive uncoupling of the partial discharge pulse
- inductive uncoupling of the partial discharge pulse
- high-frequency measurement of the partial discharge pulse in the Gigahertz range with antenna
- automatic inception and extinction voltage determination
- automatic partial discharge peak value determination
- automatic partial discharge sum determination

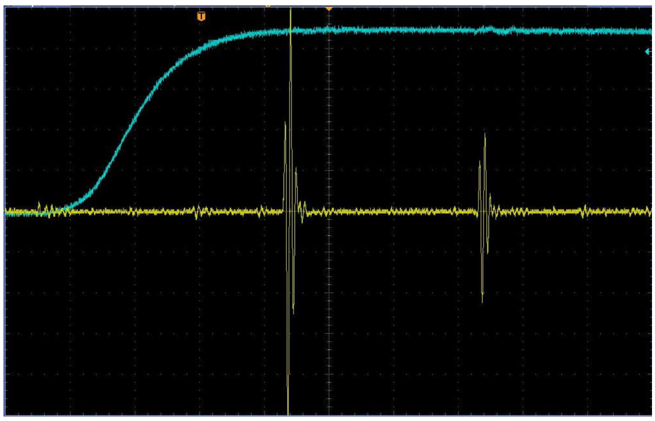
> Surge tester with partial discharge

This test technique has already been included in the SCHLEICH winding testers for the motor manufacturing for more than 10 years. Many well-known motor manufacturers trust in our technique.

Picture 16 | Partial discharge at the surge test with automatic inception and extinction voltage measurement



Picture 17 | 150nS rise time with capacitive uncoupling of the partial discharge



Picture 18 | 150nS rise time with high-frequent antenna measurement of the partial discharge

The testers MTC2 and MTC3 are characterized by the following typical features:

- surge pulse with a high rise time clearly below 200 nanoseconds according to national and international standards
- precise voltage adjustment of the surge pulse
- capacitive uncoupling of the partial discharge pulse
- inductive uncoupling of the partial discharge pulse
- high-frequency measurement of the partial discharge pulse in the Gigahertz range with antenna

- automatic inception and extinction voltage determination
- automatic partial discharge peak value determination
- automatic partial discharge sum determination

> Experiences and conclusion

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 automatic. 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.

SCHLEICH covers the VDE 530-18-41 (IEC60034-18-41) and the IEC TS 61934.

MTC2

MTC3

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

> Literature

Some information was taken from the following references:

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Editors:
Dipl.-Ing. Jan-Philipp Lahrmann
Dipl.-Ing. Martin Lahrmann
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