Influence of fast switching semiconductors on the winding insulation system of electrical machines

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***Abstract*-Variable speed and low voltage electrical drives are commonly operated by frequency converters. According to recent developments [1-2], there is a trend in the area of semi-conductors, that switching frequency and voltage slew rate will increase significantly. The aim of these semiconductors is to reduce the switching losses and to increase the switching frequency, which enables to reduce the size of passive components in the power-electric circuit. This results in less material effort and lower cost, for the power electronic component. However, electric motors operated by large slew rate inverters show particular problems in the winding insulation, which have to be analyzed. Such problems are well known for high voltage machines. Due to the increasing slew rate, this problematic occurs in low voltage machines now as well. Here, the influence of fast switching semiconductors on the winding insulation system is studied, using accelerated ageing tests with fast switching high-voltage generators.**

Keywords— Life time, winding insulation system, partial discharge, SiC semiconductors

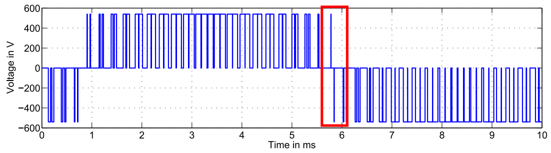
I. INTRODUCTION

According to recent developments in power semiconductor technology, particularly in the area of wide bandgap semiconductors, the switching frequency and the slew rate of the voltage will increase significantly. State of the art silicon carbide SiC MOSFETs generate slew rates of $du/dt \approx 20$ kV/µs, which stimulate harmonics in the range of approx. 10 MHz [3-4]. From the state-of-the-art silicon-based IGBT inverter systems, the following three parasitic effects, which might endanger the drive system are already well known [5-6]:

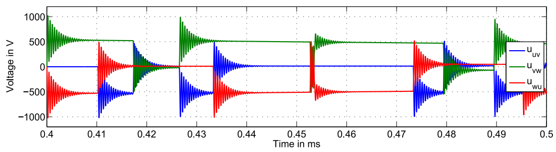
1. Travelling wave phenomena, which result in high overvoltage at the terminals of the machine (cp. fig. 1),
2. Parasitic high frequency currents caused by the high du/dt of the "common-mode" inverter output voltage and
3. Line-conducted and radiated HF electromagnetic signals in the MHz-range.

The motors supply voltage represented in the frequency domain consists of three parameters: basic frequency, switching frequency and the frequency components due to the voltage slew rate. The insulation system of electrical machines as the most important part for the reliability experiences a deterioration by a combination of ageing mechanisms. The dominant ageing mechanisms are thermal, mechanical, ambient- and electrical loads [7].

In low voltage machines, which are operated by sinusoidal



a) Idealized PWM voltage (4 kHz): line-to-line.



b) Simulated PWM voltage (16 kHz): line-to-line.

Fig. 1. Simulated PWM voltages for a two-level three-phase inverter with 540 V DC link voltage at a star-connected three phase winding system.

voltages or low switched dc voltages, deterioration by temperature is the dominant ageing factor for the winding system. Therefore, ageing by high electric fields (e.g. partial discharges) is usually not considered. The insulation systems for low voltage machines are typically defined as being not partial discharge (PD) resistant. For this reason, the machine designer and manufacturer must avoid partial discharges during the entire service life of the drive system, which is discussed in the standards [8] and [9] for different winding types. Standard [8] describes a methodology to calculate the maximum voltage amplitude for an example of a two-level inverter operating on a three-phase grid (cp. TABLE I). According to the standard the stress by overvoltage can be separated into stress categories depending on the overshoot OF = u_{pk}/u_{dc} and the impulse rise time t_r. When compared to the state of the art semiconductors the stress category must be assumed to be extreme (D) for a rise time t_r<0.1 µs of modern SiC semiconductor.

TABLE I. STRESS CATEGORIES FOR INSULATION SYSTEMS [8].

Stress category	**Overshoot factor ($p.u. u_{pk}/u_{dc}$)**	**Impulse rise time t_r in µs**
A-Benign	OF ≤ 1.1	$1 < t_r$
B-Moderate	1.1 < OF ≤ 1.5	$0.3 \leq t_r < 1$
C-Severe	1.5 < OF ≤ 2.0	$0.1 \leq t_r < 0.3$
D-Extreme	2.0 < OF ≤ 2.5	$0.03 \leq t_r < 0.1$

The combination of high overvoltage and high safety factors according to the standards lead to high test-voltages, which increase the requirements on the insulation system being free of partial discharges. The technological improvements of switching losses by fast switching semiconductors, the increase of dc link voltages and the development of corona resistant wire enamels with inorganic nano-particles and composites [10] moves the topic of electrical ageing by partial discharges into focus for low voltage machines. The technological question which must be answered is, whether the existing insulation systems must be improved to be PD free or PD resistant. To answer this question, the influence of the high loads due to fast switching has to be studied and analyzed in detail.

II. Methodology

Figure 2 presents the measurement configuration to investigate the electrical ageing of winding insulation probes. For this, a special high slew rate pulse voltage generator (cp. fig. 7) is developed at IEM, the Institute of Electrical Machines of RWTH Aachen University, which allows to vary the parameters of slew rate, switching frequency and the voltage magnitude, to adjust the desired load. To detect the PD-characteristics during the electric load, a high frequency oscilloscope is used with the antenna of a commercial winding test system for end-of-line tests (Schleich MTC 3). This device captures the electromagnetic waves which are caused by PD. Using the measurement configuration, the voltage threshold where PDs start to occur is determined for different probes of enameled wire.

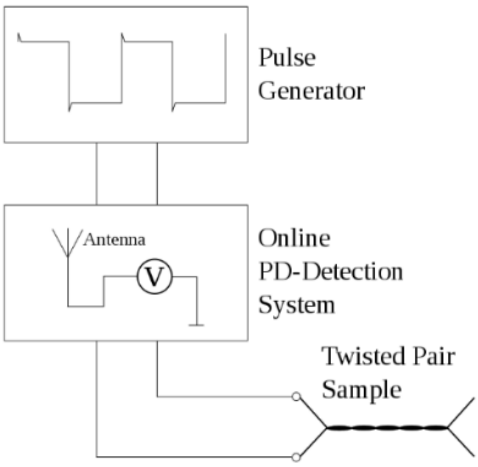


Fig. 2. Measurement configuration consisting of a pulse generator, an online PD-Detection System and a twisted pair probe of enameled wires.

III. Design of specimens

To imitate the setup of the interturn insulation of machine windings different models of enameled copper wires can be used. The most common model is a twisted pair (cp. fig. 3) of enameled copper wires for a better comparability to standard tests [11]. Depending on the nominal diameter of an enameled wire, standards define different mechanical and electrical requirements.

To consider that thicker wires may be wound with a larger force, the specimens are twisted with different pulling forces during their set-up (TABLE II. This results into higher pressure forces between the wires with increasing diameter.

TABLE II. Load and number of Twists For Twisted pairs [11].

Nominal diameter in mm	Load in N	Number of twists
0.50 – 0.71	7	12
0.71 – 1.06	13.5	8
1.06 – 1.40	27	6
1.40 – 2.00	54	4

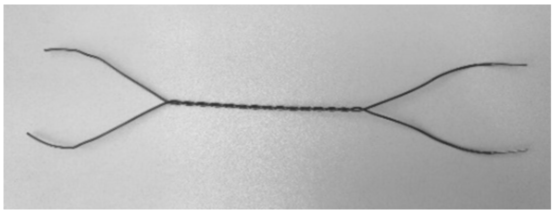


Fig. 3. Geometry of investigated twisted wire probes.

$$n \geq \frac{\left(z_{1-\alpha/2} \cdot \sigma\right)^2}{e^2} \qquad (1)$$

Requiring a maximum error e of 5 %, a confidence level of 95 % ($z_{1-\alpha/2} = 1.96$) and assuming a standard deviation σ of 10 %, the minimum number of samples n must be 15. In this study, n=20 samples of each enameled wire are chosen to increase the confidence level of the results. The specimens are tested with different voltage shapes under defined conditions (20 °C (68 °F), 50 % r.H.). For measurements with sinusoidal voltage with a frequency of 50 Hz (slew rate ≈ 1V/µs) and unipolar surge voltages (slew rate ≈ 20 kV/µs) a commercial stator analyzer according to standard [12] is utilized. The different voltage shapes are displayed in fig. 4

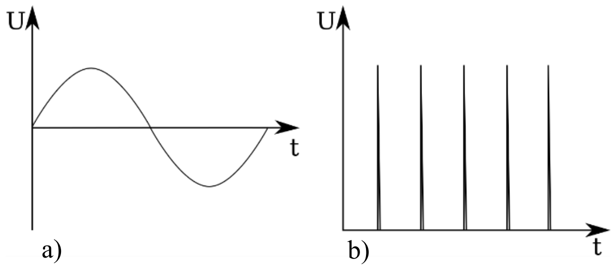


Fig. 4. Shape of test voltage of standard winding tester a) sinusoidal test voltage and b) unipolar surge voltage.

According to IEC 60034-18-41 [8] both voltage shapes are suitable to evaluate the performance of insulation systems for inverter driven electrical machines. Effects such as voltage overshoot and reflection of electromagnetic waves are considered by a series of experience based factors that are multiplied by the dc-link voltage.

The source of the standard winding test system provides up to 5 pulses per second in the unipolar surge voltage mode.

In this study, two types of wires are studied. The wire's properties are listed in TABLE III. Both, wire enamels consist of a polyester imide basecoat and a polyamide imide topcoat. For the grade 3 wire nano-particles made of Cr_2O_3 are added to the topcoat to improve the PD-resistance. The samples are chosen to study the influence of an increased coating layer and to take electrical aging of PD-resistant materials into consideration.

IV. Initial measurements

For sinusoidal voltages, the partial discharge inception voltage (PDIV) is measured by exposing a specimen to the output voltage of the measuring system. The amplitude of the voltage is increased until PD is detected. The lowest voltage that leads to PD is the PDIV. This procedure is performed for the 20 specimens of each wire. The results for this measurement are collected in fig. 5. Here, the mean partial discharge inception voltage (PDIV) is 1458 V for the wire with a grade 2 enamel and 2039 V for the grade 3 enamel, which is about 40% higher. Also the lowest measured PDIV for the grade 3 wire (1680 V) is significantly higher than the minimum PDIV for the grade 2 wire (968 V).

Regarding the repetitive partial discharge inception voltage (RPDIV) for the pulsed unipolar surge voltage measurement (The lowest voltage where at least half of the pulses of the same amplitude cause PD) the increase of the mean RPDIV is less significant: from 2029V for grade 2 to 2131 V for grade 3 which is only 5 %. Also the minimum RPDIV only changes from 1407 V to 1461 V. While for the sinusoidal test-voltage an increase of the grade of the insulation yields significantly higher PDIVs. For the pulsed unipolar surge voltage there is no reliable

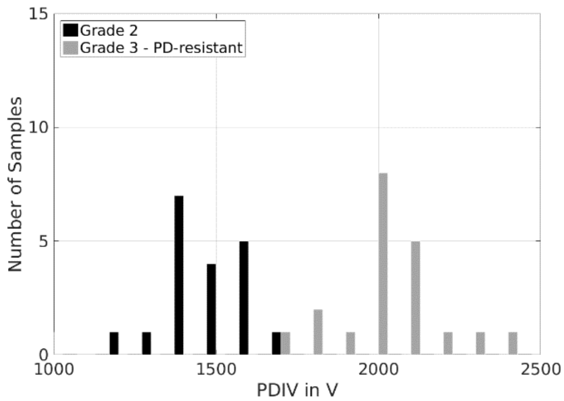


Fig. 5. Measured PIDV for sinusoidal test voltage of a grade 2 enameled wire and a corona resistant grade 3 enameled wire.

correlation between increase of the PDIV and insulation grade to be identified (cp. fig. 6). These results lead to the conclusion that considering effects that are due to a pulse shaped voltage with a high du/dt by using standardized measurement systems with sinusoidal voltages with increasing magnitude or pulsed unipolar surge voltage, is not a valid option for a reliable analysis of the winding insulation system.

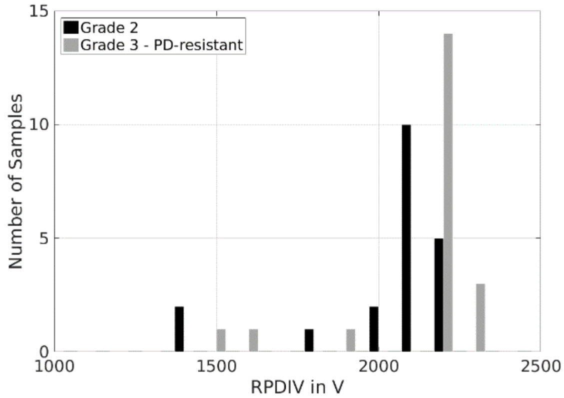


Fig. 6. Measured RPIDV for pulsed unipolar surge voltages of a grade 2 enameled wire and a corona resistant grad 3 enameled wire.

TABLE III. Properties of enamellel wires

Grade	Nominal diameter in mm	Corona resistant
Grade 2	0.56	no
Grade 3	1.0	yes

Applying this approach would mislead to the conclusion that also for pulse voltages a grade 3 enameled wire yields significantly higher PDIVs than a grade 2 wire. Inverters employing SiC-semiconductors can provide slew rates of more than 50 kV/µs and significantly higher switching frequencies as the standard measurement test system. As SiC-inverters are considered to be an important component in future drive systems, the behavior of enameled wires under such an inverter load has to be studied. For this purpose, a pulse voltage generator is developed and a test procedure is set-up.

V. High slew rate pulse voltage generator

The voltage generator that is developed at IEM is displayed in fig 7. It can provide unipolar and bipolar pulses. Amplitude, switching frequency and slew rate are displayed in TABLE IV. The parameters can be varied independently. For initial tests the generator is operated with a twisted pair specimen. For an output voltage of 1200 V and a switching frequency of 20 kHz the voltage and current output is measured during the test and displayed in figures 8 and 9.

TABLE IV. PARAMETERS OF THE PULSED VOLTAGE OF THE IEM-PULSE-VOLTGAE-GENERATOR

Parameter	Minimum value	Maximum value
Voltage Amplitude	-1200 V	1200 V
Switching Frequency	1 Hz	100 kHz
Slew rate	10 kV/ µs	50kv/ µs

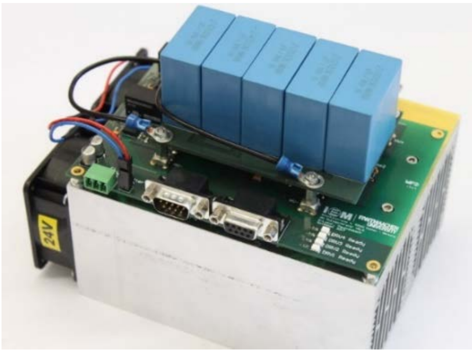


Fig. 7. Developed SiC high slew rate pulse voltage generator.

It can be seen that each voltage pulse causes a current pulse which decays within 20 ns. From fig. 9 can be taken, that the pulse starts as soon as the voltage starts to increase. This is caused by the capacitances of the specimen. It can be detected that the specimen is operated under the condition of PD. Under the influence of partial discharge, the insulation ages rapidly, causing at the end an electric breakdown. Such a breakdown is finally characterized by a short circuit between the two wires which occurs after PD breaks the insulation material. At this point the remaining life time is zero.

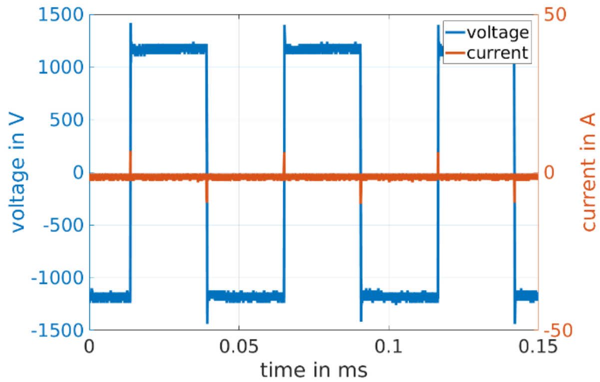


Fig. 8. Measured voltage an current of the high slew rate pulse voltage generator, operated with a twisted pair specimen.

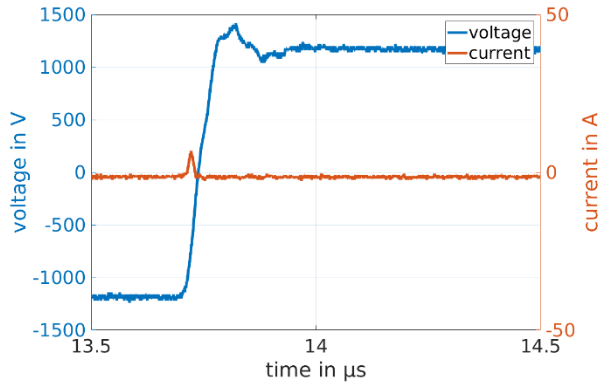


Fig. 9. Measured voltage step and current of the high slew rate pulse voltage generator.

In this case the current rises very strong (fig. 10). The breakdown occurs at 200 µs. The current rises to more than 50 A, which is the maximum current that can be detected by the measuring system used.

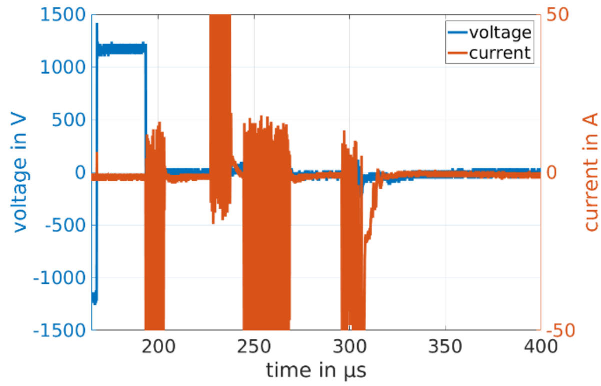


Fig. 10. Measured voltage step and current of the high slew rate pulse voltage generator, operated with a twisted pair specimen.

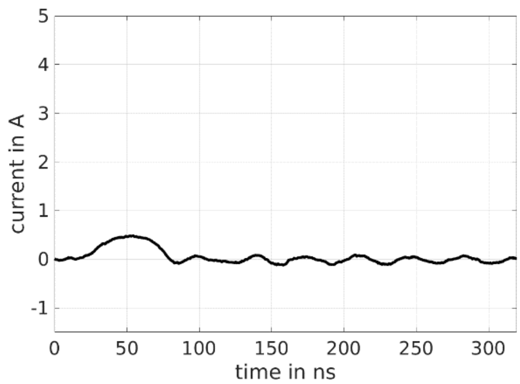


Fig. 11. Current for a PD-free specimen.

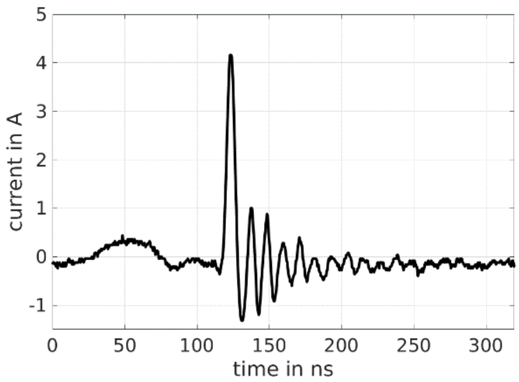


Fig. 12. Current for a specimen where PD occurs at 120 ns.

The developed measuring system is equipped with a current sensor, which provides a bandwidth of 120 MHz to detect PD. In fig 11 and 12 the measured currents for a specimen that is PD-free and a specimen where PD occurs are displayed. At the time 0 s, the voltage slope is initialized. For the specimen that is PD-free (fig. 11) a capacitive current with a rise time of 35 ns is measured. For the specimen which is exposed to PD (fig. 12), this current is superposed with high current peaks with a significantly lower rise time of 8 ns. The magnitude of the current peaks that indicates PD is limited to 4… 5 A and therefore significantly lower than the aforementioned currents of more than 50 A that occur at a breakdown (cp. fig 10).

VI. Electrical Ageing

Besides evaluating PDIVs the setup can be used to perform accelerated electrical ageing tests. It is well known that the service life of conventional enameled wires under the influence of PD is reduced to a few hours. Therefore, winding systems of machines equipped with standard enameled wires are always designed to be PD-free.

TABLE V. Life expectancies of enamelled wires under the influence of PD [13]

Enameled wire	Life expectancy in h
Grade 2 Standard	0.7
Grade 3 standard	4
Grade 2 PD-resistant	221
Grade 3 PD-resistant	>500

New insulation materials are mixed with inorganic nano-particles made of Cr_2O_3. The life-time reduction of these wires due to PD is not as severe as for standard wires. In TABLE V the life expectancy of standard wires and PD-resistant wires is compared. The data are taken from a datasheet of a manufacturer of enameled wires. However, the data are only provided for one point of operation. Here, at 16 kHz and 2.4 V peak to peak and an unknown slew rate. To estimate if machines with PD- resistant wires can be operated at voltages that exceed the PDIV, the ageing

TABLE VI. Parameters of the testing voltage for the measuring sereis with a varied frequency [13]

Parameter	Value
Voltage amplitude	Bipolar voltage of 1200V (ΔV=2400V)
Slew rate	45 kV/ µs
Frequencies	10, 20, 40 kHz

behavior of these new generation enameled wires under the influence of PD must be studied.

For a first measuring series the dependency of the frequency on the time to failure is examined. For this purpose, a standard non-PD-resistant enameled wire is studied. In TABLE VI the parameters of the pulsed testing voltage are displayed. Voltage amplitude and slew rate are kept constant, while the frequency is varied. In our experiment 5 twisted pair specimen are exposed to the test voltage for each measured frequency. The resulting time to failure is displayed in fig. 13. Due to the overshoot most of the PD occur during the voltage slope. Therefore, it is expected that the time to failure decreases reciprocally in the proportion the frequency increases. The measured data however suggest that the lifetime decreases super-linear. This may be accounted to the fact that the PD creates a loss power which leads to an increase of the specimen’s temperature.

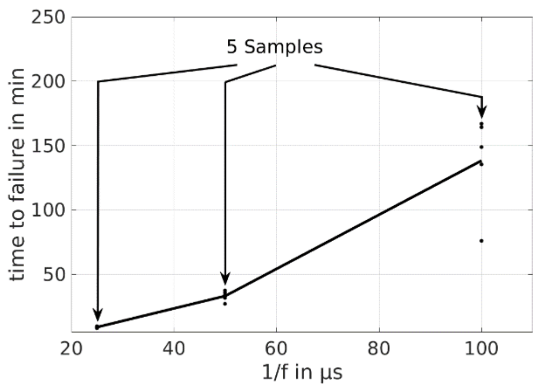


Fig. 13. Time to failure of the specimen for a variation of switching frequency.

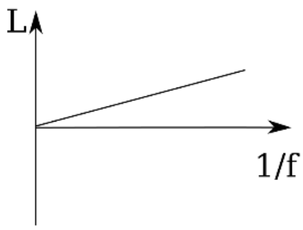
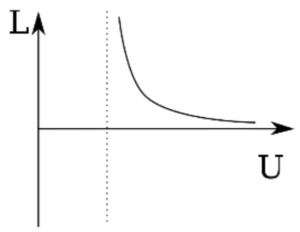
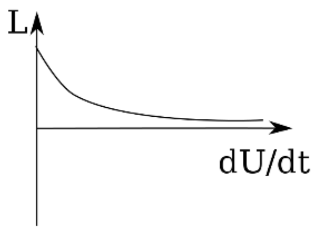
The high local temperatures lead to a further decrease of the time to failure. The temperatures of the specimen are measured using an infrared camcorder. The results are displayed in TABLE VII.

TABLE VII. Temperature of the specime in dependance on the Frequency

Frequency in kHz	Temperature in °C
10	60
20	115
40	250

For a Frequency of 40 kHz the temperature is significantly higher than the index temperature of the enamel of 200 °C. Therefore, it can be stated that the insulation material decays not only due to PD but also due to temperature effects. The influence of a varying voltage amplitude and slew rate can be studied by employing the developed high slew rate pulse voltage generator. As for the detection of the PDIV, the parameters of the output voltage are varied separately. Qualitatively the results from TABLE VIII are expected.

TABLE VIII. EXPECTED INFLUENCE OF THE PULSE-VOLTAGE-PARAMETERS ON THE LIFE EXPECTANCY OF ENAMELED WIRES

Parameter variation	**Expected influence on the life time**
Increase of the switching frequency  	Decrease of the service life
Increase of the voltage amplitude  	Decrease of the service life/ below the PDIV the lifespan is significantly larger than above it.
Increase of the slew rate  	Decrease of the service life

I. RESULTS

In this paper it is shown that for sinusoidal voltages the PD-inception voltage increases significantly when a grade 2 wire is substituted with a grade 3 wire. However, for the standard pulsed unipolar surge voltage there is no reliable correlation between insulation grade and RPIDV.The standard sinusoidal voltage test as well as the pulsed unipolar surge voltage are not a suitable means to identify the PDIV for inverter operated electrical machines.

The developed high slew rate pulse voltage generator is capable to load a winding system for a test varying the relevant parameters such as frequency, slew rate and peak voltage.

To guaranty long-life time for the winding system a PD-resistant system can be designed. To characterize the ageing behavior of the winding specimens the high slew rate pulsed voltage generator can be employed. PWM signals can be analyzed which promise better PD resistivity. The methodology discussed in this paper can be applied to answer the question if PD-resistant materials are a suitable approach to design machines for the operation with fast switching SiC-inverters.

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