

DOI 10.24425/ae.2020.131767

Low voltage winding insulation systems under the influence of high du/dt slew rate inverter voltage

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(Received: 09.09.2019, revised: 22.10.2019)

Abstract: Variable speed and low voltage electrical drives are commonly operated by frequency converters. According to recent developments, 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 high slew rate inverters show 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 nowadays 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.

Key words: life time, partial discharge, SiC semiconductors, winding insulation system

1. 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 [1, 2]. State of the art silicon carbide SiC MOSFETs generate rise times of less than $t_r = 30$ ns [3] resulting in slew rates of $du/dt \approx 20$ kV/ μ s, which stimulate



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harmonics in the range of approx. 10 MHz [4, 5]. 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 [6, 7]:

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 low risetimes t_r and high slew rates du/dt of the “common-mode” inverter output voltage.
3. Line-conducted and radiated HF electromagnetic signals in the MHz-range.

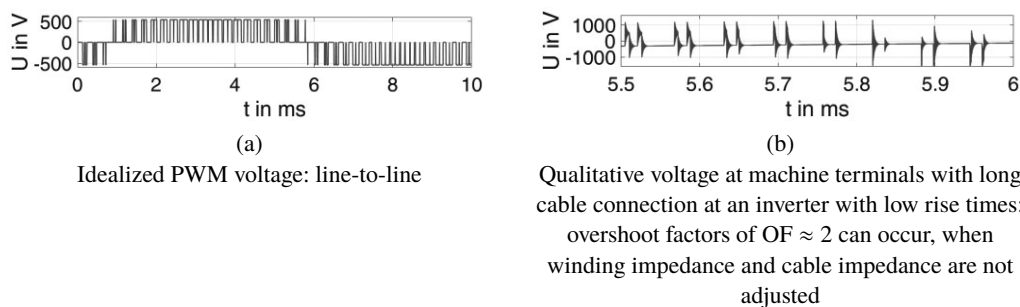


Fig. 1. Simulated PWM voltages for a two-level three-phase inverter with 540 V DC link voltage at a star-connected three phase winding system

Particularly for rise times $t_r < 200$ ns oscillation processes of parts of the winding can occur [8]. A further decrease of the rise time can stimulate additional oscillation processes.

The motor's 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 [9].

In low voltage machines, which are operated by sinusoidal or block switched dc voltages, deterioration of the winding's insulation system by temperature is the dominant ageing factor. Ageing of the insulation system by high electric fields (e.g. partial discharges) is usually only considered in high voltages machines [10]. The insulation systems for low voltage machines are therefore typically defined as being not partial discharge (PD) resistant. For this reason, the designer and manufacturer of low voltage traction drives must avoid partial discharges during the entire service life of the drive system, which is discussed in [11]. Standard [11] also 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 1). 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 $t_r < 0.1$ μ s of a modern SiC semiconductor.

At the same time the dc-link voltage in electric vehicles is increasing to allow for higher power levels and shorter charging cycles [12]. The combination of increasing dc-link voltage, high overvoltage and high safety factors according to the standards lead to high test-voltages,

Table 1. Stress categories for insulation systems [9]

Stress category	Overshoot factor (p.u. u_k/u_{dc})	Impulse rise time t_r in μs
A – benign	$OF \leq 1.1$	$1 < t_r$
B – moderate	$1.1 < OF \leq 1.5$	$0.3 \leq t_r < 1$
C – severe	$1.5 < OF \leq 2.0$	$0.1 \leq t_r < 0.3$
D – extreme	$2.0 < OF \leq 2.5$	$0.05 \leq t_r < 0.1$

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 nanoparticles and composites [13] move 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 partial discharge (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. In [14, 15] the lifetime of standard enameled wires is studied using unipolar and bipolar voltages with frequencies of up to 5 kHz. In [16, 17] a standard enameled wire is compared to three different PD-resistant wires under various voltage waveforms at frequencies of up to 10 kHz. Compared to the standard wire the PD-resistant versions show less PD-activity. As an increase of switching frequencies is foreseeable in the future, in this paper, the lifetime of enameled wires is characterized at frequencies of up to 80 kHz.

2. Methodology

Figs. 2 and 3 present the measurement configuration to investigate the partial discharge inception voltage (PDIV) and the electrical ageing of winding insulation probes. For this purpose,

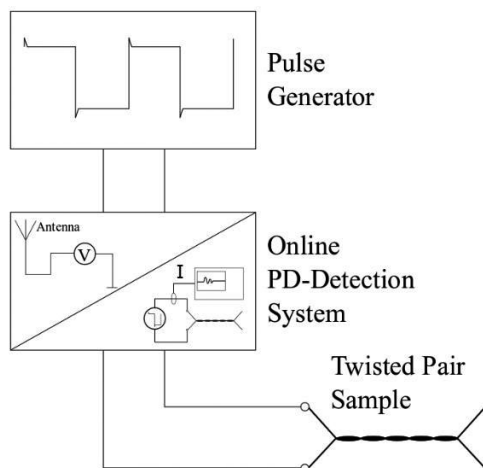


Fig. 2. Measurement configuration consisting of a pulse generator, an online PD-detection system and a twisted pair probe of enameled wires

a special high slew rate pulse voltage generator (cp. Figs. 3 and 4) is developed at IEM, the Institute of Electrical Machines of RWTH Aachen University, which allows one to vary the parameters of slew rate, switching frequency and the voltage magnitude, to adjust the desired load.

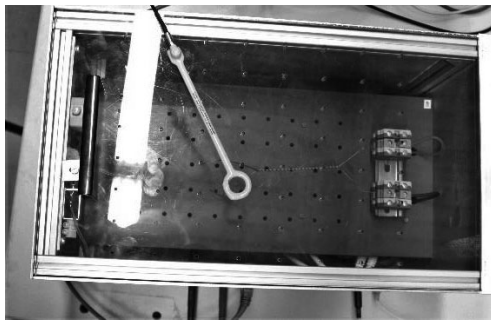


Fig. 3. Measurement setup with magnetic loop antenna for PD-detection and twisted pair specimen

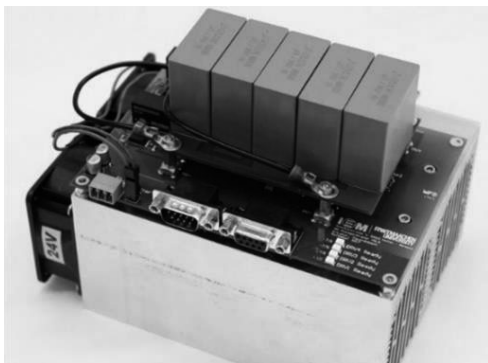


Fig. 4. Developed SiC high slew rate pulse voltage generator

To detect the PD-characteristics during the electric load, either a high frequency spectrum analyzer with an antenna is used or an oscilloscope combined with an amperemeter, measuring the current which flows into the specimen is applied. Additionally, for unipolar and sinusoidal voltages, the PDIV is measured using 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.

The voltage generator developed at IEM, which is initially presented in [18] is displayed in Fig. 4. It can provide bipolar pulses. Amplitude, switching frequency and slew rate are displayed in Table 2. The parameters can be varied independently. The generator is connected to a PC and can be operated using the software interface in Fig. 5. Using this software also the lifetime of a specimen can be recorded.

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 Fig. 6.

Table 2. Parameters of the pulsed voltage of the IEM-pulse-voltage-generator

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

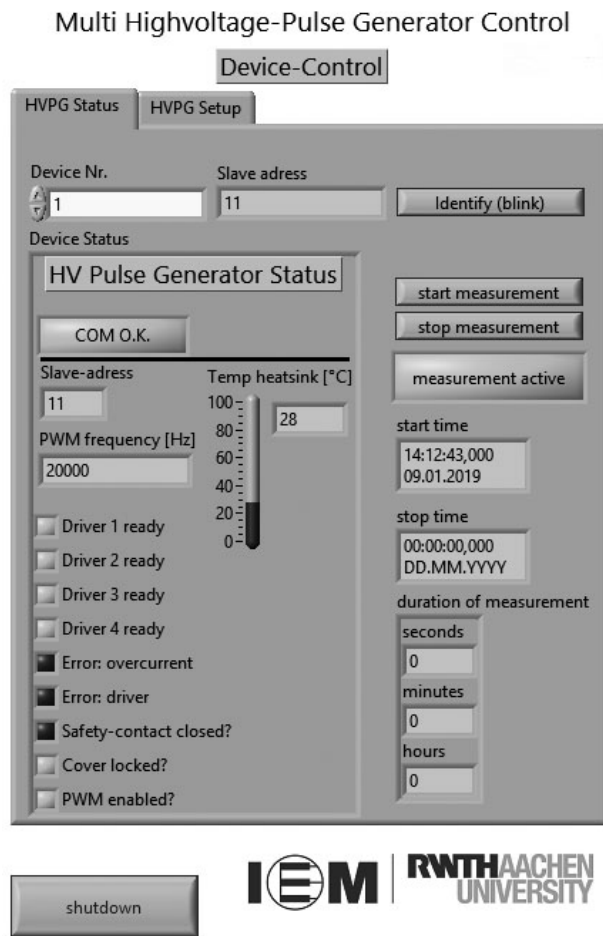


Fig. 5. User interface of the high slew rate pulse generator

It can be seen that each voltage pulse causes a current pulse which decays within 20 ns. From Fig. 6(b) can be taken, that the pulse starts as soon as the voltage starts to increase. This is caused by the capacitances of the specimen. Also a voltage overshoot can be spotted, which reaches up to 1430 V.

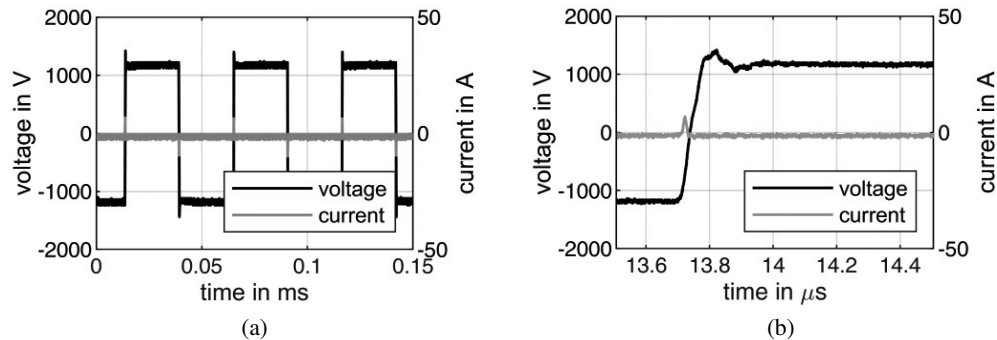


Fig. 6. Measured voltage and current of the high slew rate pulse voltage generator, operated with a twisted pair specimen for 3 periods (a) and during the voltage step (b)

This leads to an overshoot factor of 1.10. The overshoot factor depends on the voltage slew rate and the specimen under study. 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 of the conductor is zero. In this case the current rises to a high value (Fig. 7). 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. In the case of a breakdown, the output voltage of the generator is switched off automatically.

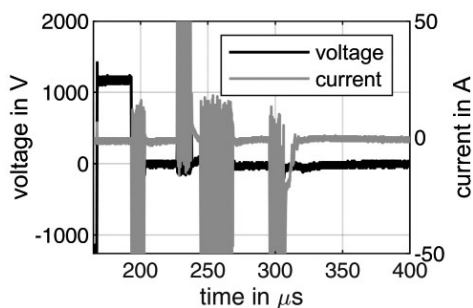


Fig. 7. Measured voltage step and current of the high slew rate pulse voltage generator, operated with a twisted pair specimen

The developed measuring system is equipped with a current sensor, which provides a bandwidth of 120 MHz to detect PD. The sensor measures the current which is flowing into the specimen. In Fig. 8 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. 8(a)) a capacitive current with a rise time of 35 ns is measured. For the specimen which is exposed to PD (Fig. 8(b)), 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. 7). Using this methodology, also the point of time where the PD occurs can be traced.

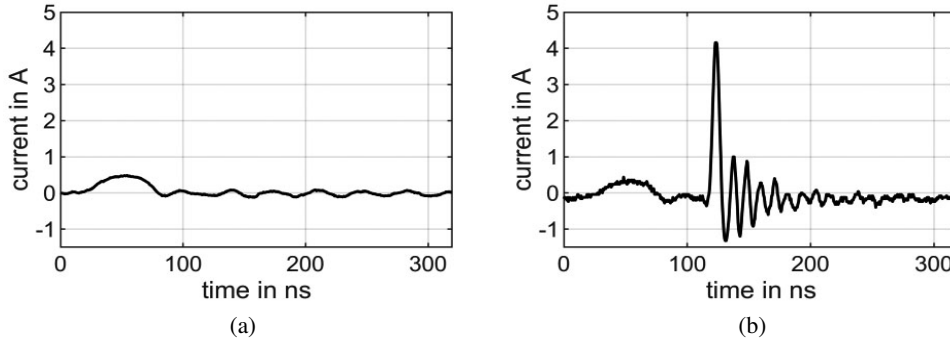


Fig. 8. Current for a PD-free specimen (a) and for a specimen where PD occurs at 120 ns (b)

For the bipolar pulse voltage, all PD signals are measured close to the maximum of the voltage that occurs due to the overshoot process. The current subsides to zero at about 250 ns.

Another methodology to detect partial discharge is employing a spectrum analyzer, equipped with an H-field antenna. The greyscale in Fig. 9 indicates the likelihood of the magnetic field strength as a function of frequency. PD-currents cause a wide-bandwidth noise signal which can be seen in Fig. 9(b), especially for frequencies between 80 MHz and 400 MHz. The advantage of this detection methodology is the larger bandwidth. Depending on the specimen PD can cause frequency components > 1 GHz. To ensure, that the wide-bandwidth signal derives from PD inside the specimen and not from PD inside the generator, the signal in Fig. 9(b) is compared to a signal which is radiated when the generator is operating at high voltages but with a specimen that is PD-free at this operating point. To minimize the influence of background noise, a nearfield antenna is employed.

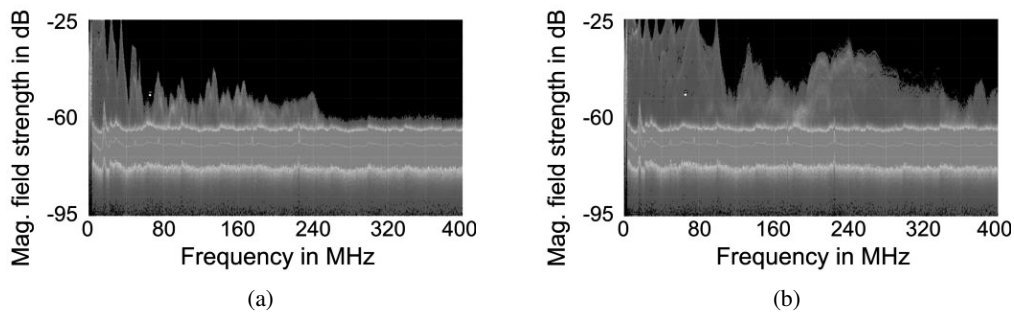


Fig. 9. Spectrum of the magnetic near field of a specimen operated in the high slew rate pulse generator without PD (a) and for a specimen where PD occurs (b)

3. 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. 10) of

enameled copper wires for a better comparability to standard tests [19]. Depending on the nominal diameter of an enameled wire, standards define different mechanical and electrical requirements.

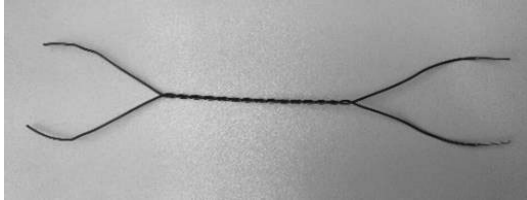


Fig. 10. Geometry of investigated twisted wire probes

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 3 displays the numbers of twists and the load which is needed to produce the specimens which are studied in this paper. This results into higher pressure forces between the wires with increasing diameter.

Table 3. Load and number of twists for twisted pairs [19]

Nominal diameter in mm	Load in N	Number of twists
0.50–0.71	7	12
0.71–1.06	13.5	8

$$n \geq \frac{(z_{1-\alpha/2} \cdot \sigma)^2}{e^2} . \quad (1)$$

According to the formulation for the margin of error for a population proportion (Equation (1)), the minimum number of samples n must be 15 when a maximum error e of 5% and a confidence level of 95% ($z_{1-\alpha/2} = 1.96$) are required and a standard deviation σ of 10% is assumed. Performing PDIV measurements 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 ≈ 1 V/ μ s) and unipolar surge voltages (slew rate ≈ 20 kV/ μ s) a commercial stator analyzer according to standard [20] is utilized. The source of the standard winding test system provides up to 5 pulses per second in the unipolar surge voltage mode.

For a bipolar pulsed voltage with $du/dt = 45$ kV/ μ s the measurement setup from Fig. 2 is used, employing the high slew rate pulse voltage generator. The different voltage shapes are displayed in Fig. 11.

According to IEC 60034-18-41 [11] voltage shapes (a) and (b) are suitable to evaluate the performance of insulation systems for inverter driven electrical machines, when twisted pair specimens are employed. The output voltage of an inverter resembles however more the square waveform of the bipolar pulse voltage (Fig. 11(c)).

In this study, two types of wires are studied. The wire's properties are listed in Table 4. Both, wire enamels consist of a polyester imide basecoat and a polyamide imide topcoat. For the wire with 0.71 mm diameter inorganic nano-particles are added to the topcoat to improve the

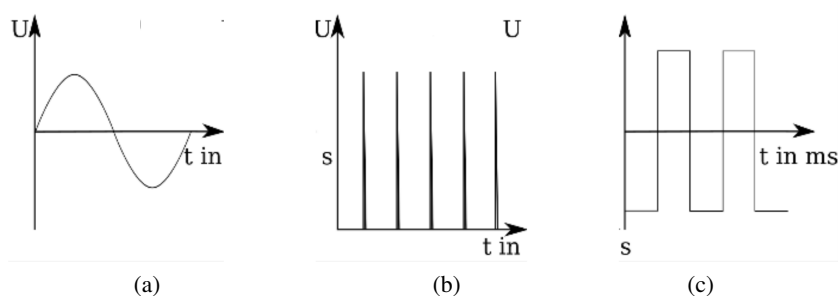


Fig. 11. Shape of test voltage of standard winding tester: sinusoidal test voltage (a); unipolar surge voltage (b); bipolar pulse voltage (c)

PD-resistance. Before testing, no preconditioning is performed as all the specimens have been stored under the exact same conditions for the prior 3 months.

Table 4. Parameters of the enameled wire which is used for electrical ageing

Standard enameled wire	
Nominal diameter	1.0 mm
Temperature index	200°C
Insulation grade	2
Measured PDIV @ $f = 20$ kHz and $du/dt = 45$ kV/ μ s	975 V
Insulation material	Polyamide imide and polyester imide
PD resistant enameled wire	
Nominal diameter	0.71 mm
Temperature index	unknown
Insulation grade	2
Measured PDIV @ $f = 20$ kHz and $du/dt = 45$ kV/ μ s	787 V
Insulation material	Polyamide imide with microfillers

4. Measurement of PDIV

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 20 specimens of each wire. The results for this measurement are collected in

Fig. 12(a). Here, the mean partial discharge inception voltage (PDIV) is 1192 V for the wire with the standard enamel and 1147 V for the PD-resistant enamel. Like the mean values, the lowest measured PDIV for the standard wire (1030 V) is in the same range as the PD-resistant wire (1074 V).

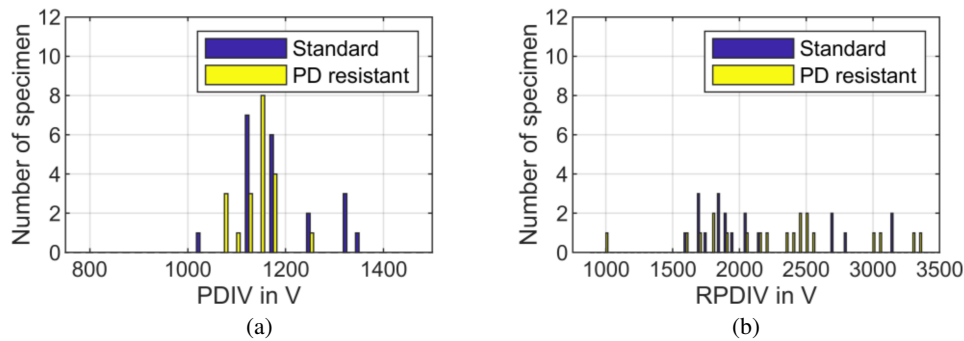


Fig. 12. PD measurement of a grade 2 enameled wire and a corona resistant grade 3 enameled wire: PDIV for a sinusoidal voltage of 50 Hz (a) and RPDIV for a unipolar pulse voltage (b)

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) it can be noted, that except for some extreme values, the RPDIVs of the wires are again in the same range (Fig. 12(b)). However, there is a large standard deviation among the specimens that are tested. The mean RPDIV is 2132 V for the standard wire and 2318 V for the PD-resistant wire.

Inverters employing SiC-semiconductors can provide slew rates of more than 50 kV/ μ s and significantly higher switching frequencies than the standard measurement test system.

Also the windings of electrical machines are generally subjected to bipolar pulse voltages. Therefore, the PIDVs of the specimen are measured using the set-up presented in Fig. 2, using the IEM SiC-generator. The resulting PDIVs are presented in Fig. 13. It can be seen that the standard wire reaches higher PDIVs (mean value 975 V) than the PD-resistant wire (mean 787 V).

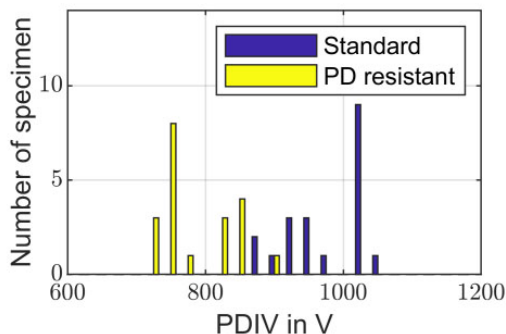


Fig. 13. Measured PDIV for bipolar pulse voltage of a grade 2 enameled wire

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 or pulsed unipolar surge voltage, is not a valid option for a reliable analysis of the winding insulation system.

5. 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.

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

Table 5. Life expectancies of enameled wires under the influence of PD [21]

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

For a first measuring series, the dependency of the frequency on the time to failure is examined. For this purpose, the standard enameled wire and the PD-resistant wire are compared. In Table 6 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 specimens of the standard enameled wires and 3 specimens of the PD-resistant wire are exposed to the test voltage for each measured frequency. The resulting time to failure is displayed in Fig. 14.

To model during electrical ageing the inverse power model can be applied [8, 17]:

$$U_{b1} = k_b n_{b1}^{-1/m}, \quad (2)$$

where U_{b1} is the pulse voltage, n_{b1} is the number of pulses leading to partial discharge and k_b and m are material dependent constants.

Most of the PD activity occurs during the voltage slope. Also, for a voltage of 1.2 kV it can be shown that each voltage slope causes PD. Therefore, it is expected that the time to failure

Table 6. Parameters of the testing voltage for the measuring series with a varied frequency [18]

Parameter	Value
Voltage amplitude	Bipolar voltage of 1200 V ($\Delta V = 2400$ V)
Slew rate	45 kV/ μ s
Frequencies	10, 20, 40 kHz

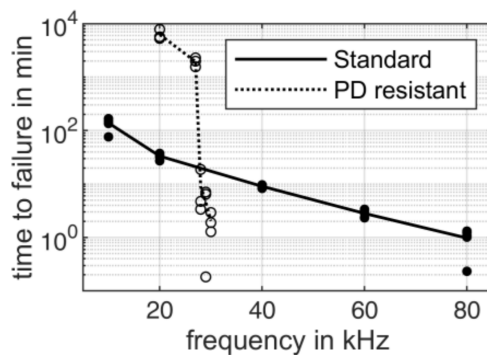


Fig. 14. Measured PDIV for bipolar pulse voltage of a grade 2 enameled wire

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. Also, frequency dependent polarization losses increase the temperature at high frequencies.

For a frequency of 40 kHz the temperature of the standard wire 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 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 7.

Table 7. Temperature of the specimens in dependence on the frequency

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

For the PD-resistant wires the lifetime decreases drastically for frequencies above 27 kHz. For these high frequencies, the enamel is significantly darker after testing than before testing. This leads to the conclusion that the thermal load destroyed the enamel. Measurements using

the infrared camcorders are not performed for these load points as it cannot be guaranteed that a steady state is reached. The influence of a varying voltage amplitude and slew rate can be studied by again employing the developed high slew rate pulse voltage generator.

In Fig. 15(a) the measured lifetime of the specimens with standard enameled wires is displayed for different voltages at a frequency of 20 kHz.

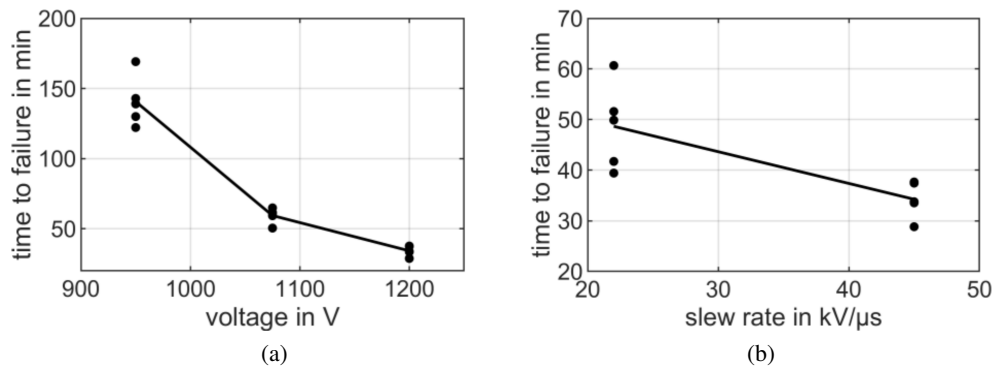


Fig. 15. Time to failure of the specimen for a variation of voltage (a) and slew rate (b)

The voltage regarded here is not the peak voltage, which can be found in Fig. 6, but the voltage in a steady state. The average measured PDIV of 5 specimens of the enameled wires at 20 kHz and a du/dt of 45 kV/μs is 872 V. The lowest voltage for the lifetime measurement is chosen to be 950 V to ensure that all specimens are operated under the influence of PD during the entire lifetime test. The lifetime of the wires decreased to 140 min at this operating point, which underlines why PD must be avoided in traction motors. The inverse power model (2) can also be applied to characterize the voltage dependence of the lifetime.

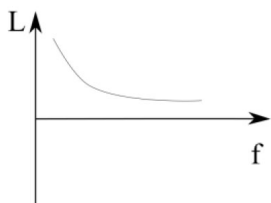
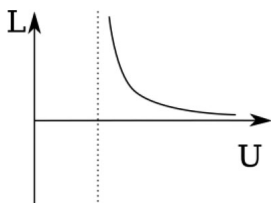
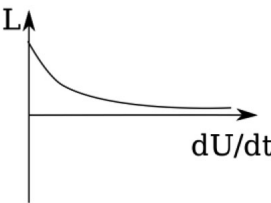
The voltage slew rate (du/dt) can also be varied. Here the lifetime is investigated at two different slew rates (Fig. 15(b)). An increasing slew rate leads to shorter lifetimes. As mentioned before, changing the slew rate, leads also to a different overshoot factor. The overshoot factor is 1.04 for a slew rate of $du/dt = 22$ kV/μs and 1.10 for a slew rate of $du/dt = 45$ kV/μs.

As for the detection of the PDIV, the parameters of the output voltage are varied separately. Qualitatively the results from Table 8 are expected. The data from the measurements confirm the qualitative tendencies from Table 8. The variation of the frequency shows, however, a more significant influence on the lifetime than the predicted linear relation.

6. Results

In this paper the PDIVs of a PD-resistant grade 2 wire and a grade 2 wire with the standard enamel are compared. For sinusoidal voltages, both types of specimens achieve similar PDIVs. However, for the standard pulsed unipolar surge voltage there is no reliable correlation between insulation grade and RPDIV. As both test voltages do not resemble an inverter load PDIV is also measured at a bipolar pulse voltage, using the IEM built HV-SiC-generator. The PDIVs that are

Table 8. 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
	

measured for the PD-resistant wire in this case are smaller than for the standard wire. The standard sinusoidal voltage test as well as the pulsed unipolar surge voltage are therefore 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 guarantee a 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 promises 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. For the specimens that are studied in this paper it is shown, that the lifetime advantage of the PD-resistant wire only exists below a frequency threshold. Above this frequency there is a drastic drop of the lifetime making the given enameled wire unsuitable for an operation at simultaneously high frequencies and high voltages.

References

- [1] Wrzecionko B., Biela J., Kolar J.W., *SiC Power Semiconductors in HEVs: Influence of Junction Temperature on Power Density, Chip Utilization and Efficiency*, 2009 35th Annual Conference of IEEE Industrial Electronics, Porto, pp. 3834–3841 (2009).
- [2] Bortis D., Wrzecionko B., Kolar J.W., *A 120°C ambient temperature forced air-cooled normally-off SiC JFET automotive inverter system*, IEEE Transactions on Power Electronics, vol. 29, no. 5, pp. 2345–2358 (2014).
- [3] Harada K., Maki K., Pounyakhet S., Tokiyoshi J., Kozako M., Ohtsuka S., Hikita M., *Switching characteristics of SiC-VJFET and manufacture of inverter*, The 2010 International Power Electronics Conference – ECCE ASIA, Sapporo, pp. 176–179 (2010).
- [4] Köneke T., Mertens A., Domes D., Kanschat P., *Highly Efficient 12kVA Inverter with Natural Convection Cooling Using SiC Switches*, International conference, Power Electronics, Intelligent Motion and Power Quality (PCIM), Nuremberg (2011).
- [5] Biela J., Schweizer M., Waffler S., Kolar J.W., *SiC versus Si-Evaluation of Potentials for Performance Improvement of Inverter and DC-DC Converter Systems by SiC Power Semiconductors*, IEEE Transactions on Industrial Electronics, vol. 58, no. 7 (2011).
- [6] Gong X., Ferreira J.A., *Comparison and Reduction of Conducted EMI in SiC JFET and Si IGBT-Based Motor Drives*, IEEE Transactions on Power Electronics, vol. 29, no. 4 (2014).
- [7] Ruf A., Paustenbach J., Franck D., Hameyer K., *A methodology to identify electrical ageing of winding insulation systems*, IEEE International Electric Machines and Drives Conference, (IEMDC) Miami, FL, pp. 1–7 (2017).
- [8] Kaufhold M., Aninger H., Berth M., Speck J., Eberhardt M., *Electrical stress and failure mechanism of the winding insulation in PWM-inverter-fed low-voltage induction motors*, in IEEE Transactions on Industrial Electronics, vol. 47, no. 2, pp. 396–402 (2000).
- [9] IEC 60034-18-1:2010, *Rotating electrical machines – Part 18-1: Functional evaluation of insulation systems* (2010).
- [10] IEC 60034-18-42, *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).
- [11] IEC 60034-18-41 ed. I, *Rotating electrical machines – Part 18-41: Partial discharge free electrical insulation systems (Type I) used in rotating electrical machines fed from voltage converters – Qualification and quality control tests* (2014).
- [12] Jung C., *Power Up with 800-V Systems: The benefits of upgrading voltage power for battery-electric passenger vehicles*, IEEE Electrification Magazine, vol. 5, no. 1, pp. 53–58 (2017).
- [13] Kikuchi H., Hanawa H., *Inverter surge resistant enameled wire with nanocomposite insulating material*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 19, no. 1, pp. 99–106 (2012).
- [14] Kaufhold M., *Failure mechanism of the interturn insulation of low voltage electric machines fed by pulse controlled inverters*, Proceedings of 1995 Conference on Electrical Insulation and Dielectric Phenomena, Virginia Beach, VA, USA, pp. 254–257 (1995).
- [15] Kaufhold M., Borner G., Eberhardt M., Speck J., *Failure mechanism of the interturn insulation of low voltage electric machines fed by pulse-controlled inverters*, IEEE Electrical Insulation Magazine, vol. 12, no. 5, pp. 9–16, Sept.-Oct. (1996).
- [16] Fabiani D., Montanari G.C., Cavallini A., Mazzanti G., *Relation between space charge accumulation and partial discharge activity in enameled wires under PWM-like voltage waveforms*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 11, no. 3, pp. 393–405 (2004).

- [17] Fabiani D., *Accelerated degradation of ac-motor winding insulation due to voltage waveforms generated by adjustable speed drives*, PhD Thesis, University of Bologna (2003).
- [18] Hameyer K., Ruf A., Pauli F., *Influence of fast switching semiconductors on the winding insulation system of electrical machines*, 2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia), Niigata, Japan, pp. 740–745 (2018).
- [19] IEC 60317-0-1, *Specifications for particular types of winding wires – Part 0-1: General requirements – Enameled round copper wire* (2013).
- [20] IEC 61934, *Electrical insulating materials and systems – Electrical measurement of partial discharges (PD) under short rise time and repetitive voltage impulses* (2011).
- [21] LWW-Group: Dahrentrad Daprest 200, *Round enamelled conductor of copper, corona resistant, class 200*, datasheet.