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# A methodology to identify electrical ageing of winding insulation systems

Andreas Ruf[1], Jörg Paustenbach[1], David Franck[1] and Kay Hameyer[1]
[1]Institute of Electrical Machines (IEM), RWTH Aachen University, 52062 Aachen, Germany

*Abstract*— **Forced by the high requirements on modern variable speed controlled drives, power electronics are used to achieve the specific requirements on accuracy and dynamics. These properties are realized by fast switching converters, which result in voltages and currents with high slew rates. As a consequence, these rise times or slew rates lead to high frequency phenomena throughout the electrical drive. High frequency electrical traveling waves superimpose in the electrical machine, in the supply cables and in the power inverter. Based on this superimposition, high overvoltage occurs at different locations in the electrical drive systems [1]. These high voltage waves result in high electrical fields, which load the insulation by various ageing mechanisms [2]. Therefore, ageing of insulation in low voltage machines is influenced by a combination of the dominant factors: thermal, mechanical, electrical ageing and the interaction of their impacts. For this reason, high frequency phenomena in electrical drives lead to failures, e.g. in the winding system of electrical machines. This paper presents a methodology to identify the electrical load of insulation systems of machine windings. The methodology is based on the use of a high voltage generator. Here, a voltage generator is presented, which is used to identify the electrical ageing procedure for different winding topologies.**

***Keywords— PWM, slew ratr, ageing, insulation, machine, winding***

## I. Introduction

Due to reasons of energy efficiency and high dynamics, electrical drives are commonly supplied by frequency inverters which apply an alternating voltage system to the electrical machine by means of pulse-width modulation (PWM) based upon the fast switching of semiconductors. 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. State of the art silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs) can generate a voltage rise of up to 600 V within 30 ns, which results in a slew rate of approx. 20 kV/µs and will stimulate harmonics in the range of some 10 MHz with a concomitant overvoltage which magnitude depends upon the design of the inverter and the parasites. State of the art comparable semiconductors show a voltage rise of 600 V in 0.15 µs, which results in a slew rate of 4 kV/µs. In the frequency domain, this voltage contains three different components: fundamental frequency, switching frequency and frequency components due to the voltage slew rate. The insulation system of electrical machines is loaded by inverter voltages (Fig. 1), which are reshaped by the transmission line between the cable and the electrical machine (travelling waves, damping, etc.) [3]. It is well known that different ageing mechanisms deteriorate the insulation system of machines, depending on the specific application loads. The dominant ageing mechanisms are thermal, mechanical, ambient and electrical loads. In low voltage machines, which are operated by sinusoidal voltages, deterioration by temperature is the dominant ageing factor for the winding system [4-6]. Thus, ageing by high electric fields (e.g. partial discharges) is not considered directly for the low voltage machines. The insulation system for low voltage machines are typically defined being not partial discharges resistant. The machine designer and manufacturer must avoid partial discharges during the entire service life of the drive system, which is discussed in standards [7] and [8] for different winding types. The combination of the rising load by new fast switching semiconductors and the development of corona resistant wire enamels with inorganic nano particles [10,11] moves the topic of electrical ageing back into focus for the low voltage machines.

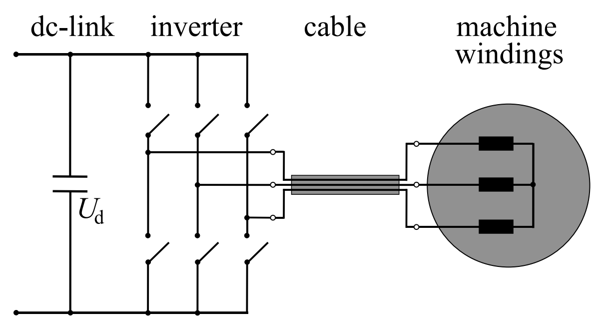


Fig. 1. Configuration of power electronics, connection by cable and machine windings.

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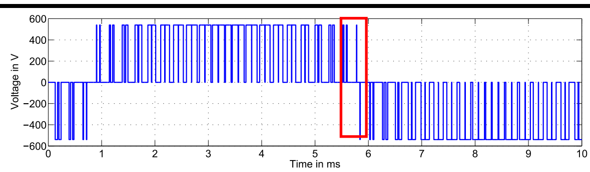
## II. SIMULATION OF ELECTRICAL LOADS

Partial discharges can occur in three different ways: corona discharges, surface discharges and void discharges. Such effects are induced by high electrical fields in inhomogeneous regions and are the reason of progressive deterioration or electrical ageing. Apart from the electrode geometry, which results in inhomogeneous field distributions, the voltage potentials must be known in the early design stage of the insulation. Standard [7] describes a methodology to calculate the maximum voltage amplitude for an example of a two-level inverter operating on a three-phase grid. These voltages depend on the intermediate circuit, grounding, transmission, and many different parameters, which require to model the drive system including assumptions on the transmission parameters. According to the standard the stress by overvoltages can be separated into stress categories depending on the overshoot $\mathrm{OF} = u_{pk}/u_{dc}$ and the impulse rise time $t_r$. Compared to state of the art IGBT semiconductors, with a voltage rise time of $t_r$≈0.15 µs the stress category must be assumed severe (C) and SiC with a $t_r$< 0.1 µs extreme (D).

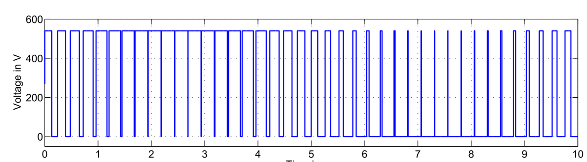
TABLE I. STRESS CATEGORIES FOR INSULATION SYSTEMS [7].

| **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 | $0.3 \le t_r < 1$ |
| C-Severe | 1.5 < OF ≤ 2.0 | $0.1 \le t_r < 0.3$ |
| D-Extreme | 2.0 < OF ≤ 2.5 | $0.03 \le t_r < 0.1$ |

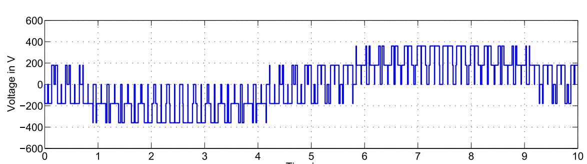
For this reason, the combination of high overshoot and safety factors lead to high values of tension, which have to be applied in order to guarantee partial discharge freedom (up to 2.5 (OF) *2 (bipolar) *1.25 (PD-Hysteresis) *1.3 (Temperature) *1.2 (ageing) = 9.75 times dc link voltage) during the entire lifetime. For semiconductors with high slew rates and dc-link voltages above several 100 V these factors seems to be unpracticable. A more practicable variant is to calculate the voltages with high frequency models, the underlying theory of identification and parametrization is presented in [13-16]. Fig. 2 shows the results of simulated voltages for a two level-inverter with a maximum 540 V dc link voltage. In the case of isolated operation e.g. in an electric car, the negative potential of the intermediate circuit is grounded. In Fig. 2 a)-c) idealized voltages with a carrier frequency of 4 kHz and natural sampling are presented. Idealized voltages are a vast simplification for real applications. For this reason, figures 2 d)-f) consider the transmission characteristics of the drive and the machine presented in [3], which leads to overvoltages by reflections and superimposition. This calculated voltage magnitudes are used to parametrize different FE-models, which depict the different electrode arrangement of a machine with distributed windings and round enameled wires. This enables to identify the electrical field maxima and the most crucial points for the insulation, which must be studied experimentally in detail. Round enameled wires are standardized in [9] by their nominal conductor diameter and their minimum insulation thickness, which are used to parametrize the FE-model in Fig. 3 a) - c). The electrical field distribution is simulated for different standard wire diameters [6] and insulation paper thicknesses.



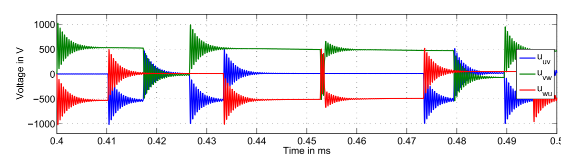

a) Idealized PWM voltage (4 kHz): line-to-line.



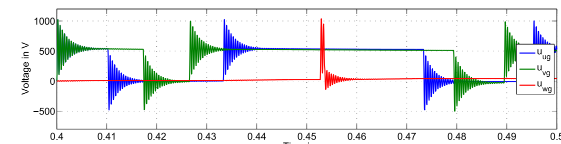

b) Idealized PWM voltage (4 kHz): line-to-ground.



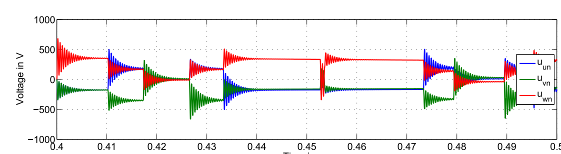

c) Idealized PWM voltage (4 kHz): line-to-neutral point.




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

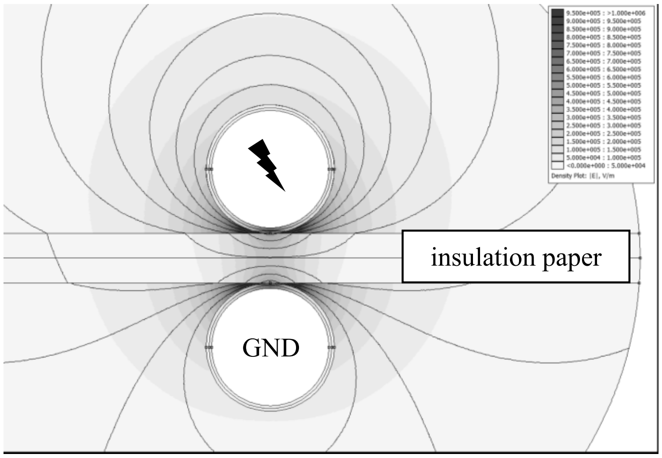



e) Simulated PWM voltage (16 kHz): line-to-ground.

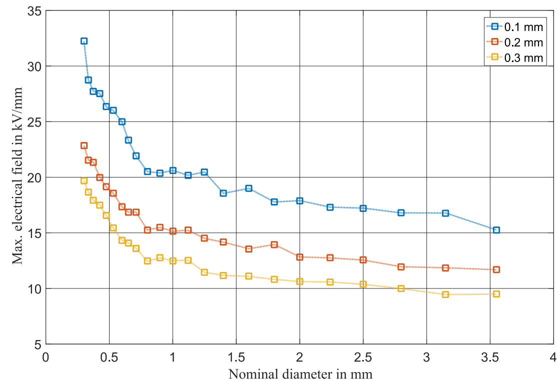



f) Simulated PWM voltage (16 kHz): line-to-neutral point.

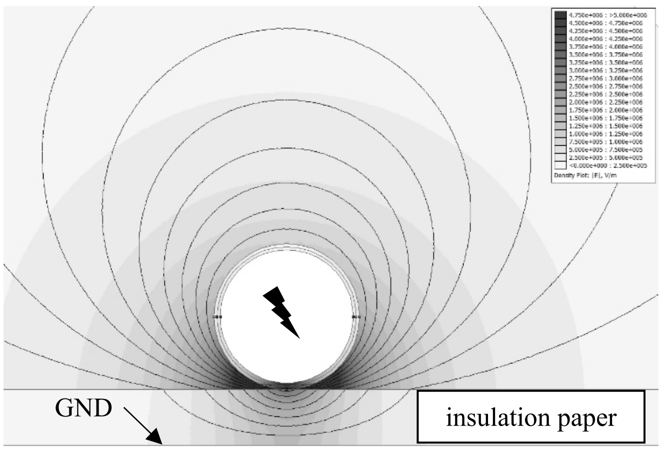
Fig. 2. PWM Voltage for a two-level inverter with 540 V dc link voltage (simulated).



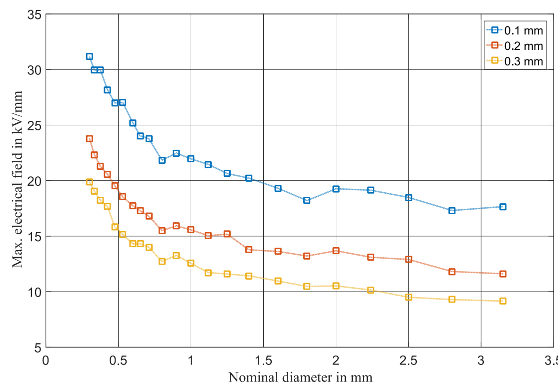

a) Phase to phase insulation with enameled wires and insulation paper.



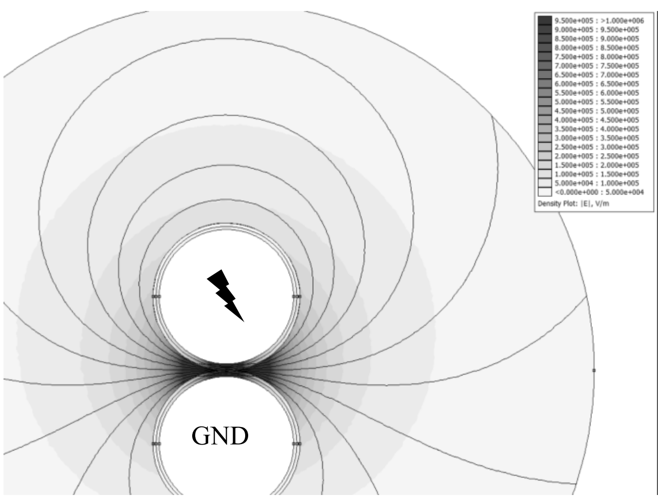

d) Maximum electrical field on the surface of enameled wires (GR2) for phase to phase insulation vs. wire diameter and paper thickness.



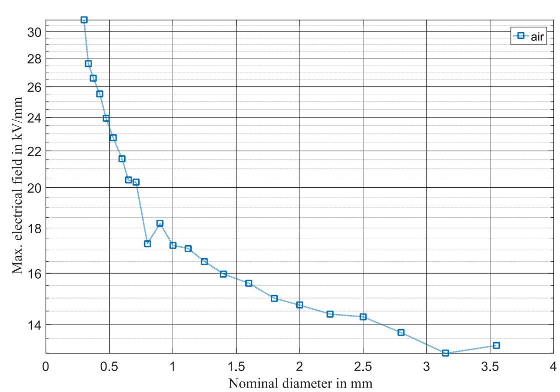

b) Phase to ground insulation with enameled wire and insulation paper.




e) Maximum electrical field on the surface of enameled wires (GR2) for phase to ground insulation vs. wire diameter and paper thickness.




c) Turn to turn insulation with two enameled wires.




f) Maximum electrical field on the surface of enameled wires (GR2) for turn to turn insulation vs. different wire diameters.

Fig. 3. Maximum electrical field strength for different geometries (simulated).

The maximum electrical field presented in Fig. 3 d) - f) is calculated at the surface of the HV-electrode. The results show a decreasing electrical field with increasing wire diameter and insulation paper thickness according to analytical estimations. The maximum electrical load can be found between the turns of isolated enameled wires and should be considered by defining the wire diameter or limiting the maximum voltage (Fig. 3 c) f)). In contrast to the winding insulation the electrical field and the probability of partial discharges can be significantly reduced by using thicker insulation papers. The phase to phase insulation presented in Fig. 3 a) is often underrated, when compared to the ground insulation of the winding. Particularly when the phase to phase voltage changes polarity the magnitude of the voltage can reach up to four times the intermediate value, which can occur twice a period of the base frequency (Fig. 2 a)). This increases the electric field above 10 kV/mm in this topology and must be considered in the early design stage of the insulation. The most crucial point is the winding or interturn insulation. Experimental investigations must be performed to identify the partial discharges inception voltages to limit the applications dc link voltage or to redesign the windings distribution. Electrical ageing or the inception voltage can be influenced by different combinations of aging mechanisms, which can have direct or indirect interactions. Different ageing models are postulated and compared in [17,18], which are all based on inverse power or exponential laws. The most common lifetime model used is presented in [19,20]:

$$L = K \cdot \left(\frac{E}{E_0}\right)^{-n} \quad (1)$$

with $K$ and $n$ as two model factors and $E/E_0$ representing the electrical field stress level. $E_0$ is the threshold electrical stress value, where the probability of partial discharges increases. $E$ and $E_0$ can be replaced by Voltages $V$ and $V_0$, where $V_0$ can be assumed to be the partial discharges inception voltage. The probabilistic threshold parameter $V_0$ depends on the entire winding insulation system, the environmental conditions just as temperature, humidity, pressure, and the state of health (SOH) of the insulating materials. To reduce the coincidence of a partial discharge, the repetitive partial discharges inception voltage is measured, to identify the maximum allowed voltage for not resistant partial discharges insulation systems. At this point, specimens must be defined to investigate the crucial parameters of interturn insulations.

TABLE II. LOAD AND NUMBER OF TWISTS FOR TWISTED PAIRS [21].

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

## III. DESIGN OF SPECIMENS

To model the interturn insulation of machine windings different models of enameled copper wires can be used. The most often used model is a twisted pair of enameled copper wires for a better comparability to standard tests [9]. Depending on the nominal diameter of an enameled wire, standards define different mechanical and electrical requirements. To incorporate 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.

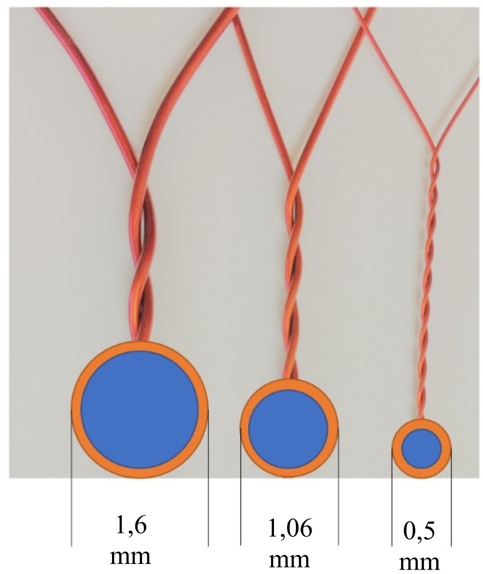



Fig. 4. Geometries of investigated twisted wire probes.

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

Requiring a maximum error $e$ of 5 %, a confidence level of 95 % ($z_{1-\alpha/2} = 1.96$) and assuming a standard deviation $\sigma$ of 10 %, the minimum sample size must be 15. In this study, 20 samples are used 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 and unipolar surge voltages (slew rate ≈ 20 kV/µs) a commercial stator analyzer according to standard [22] is utilized.

## IV. RESULTS

Fig. 6 presents the Weibull distributions for partial discharges measurements between twisted pairs of enameled wires. For sinusoidal voltages Fig. 6 a) and TABLE III. the average PDIV is in the same range (between 1326 V and 1440 V) for all nominal diameters, although it can be assumed that the PDIV decreases with the nominal diameter as much as the electrical field strength in Fig. 3 f) increases. This shows the nonnegligible effect of the force between the enameled wires, which must be assumed increasing with the winding diameter based on the increased constraints of the standards. This shows that the design of the machine insulation based only on field strength simulations is not sufficient.

The standard deviation $\sigma$ for sinusoidal PDIV is between 7.6 % and 9.7 % which coincides with the assumptions made during the specimens' design. Based on the safety requirements ($3\sigma$ for 95 %, or $5\sigma$ 99%) and the assumed safety factors (1.0-1.3(Temperature)*1.0-1.2(ageing) [7]) the maximum amplitude voltage can be calculated to avoid partial discharges during the entire lifetime. In this case, electrical ageing by erosion can be neglected as a relevant ageing factor during operation with sinusoidal voltage. The hysteresis effect for lasting partial discharges can be measured by the value of partial discharges extinction voltage, which is between 13.0 % and 18.2 % lower than the PDIV. Regarding to the defined maximum error of 5 % for the number of specimens, a safety factor of 1.25 according to standard [7] is justified.

Using the PDIV or PDEV as the critical parameter depends on the interpretation of the results. Calculating the allowed nominal dc-link voltage for the insulation system the PDEV must be used, while the PDIV identifies the maximum dc-link voltage in the transient state, which ensures a PD free operation without electrical ageing.

Comparing sinusoidal with non-uniformly voltages the occurring electrical load is different. In case of switched voltages, the stress is concentrated on the first winding. The assumption of increasing standard deviation can be confirmed (Fig. 6 b)). The methodology of identifying the repetitive PD inception voltage is presented in Fig. 5. The unipolar voltage is applied 5 times for each amplitude starting from 500 V. The voltage is increased in 50 V steps and the discharge is measured. The repetitive PD voltage is identified if a partial discharge occurs more than once. This methodology is repeated twice for each specimen (changing the HV and GND electrode). The results in Fig. 6 b) show a decreasing average of RPDIV with wire diameter, even though the electrical field strength must decrease.

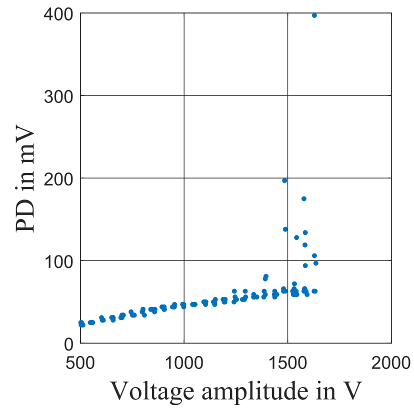



Fig. 5. Measured Partial Discharges for different Voltage amplitudes.

The standard deviation is between 359 V (16.8 %)and 413 V (22.6 %). For this reason, the electrical load of switched voltages between two turns must be kept small to prevent the winding insulation from partial discharges: Phase to phase insulation paper must be used in the endwinding and the overshoot voltage must be kept as small as possible to reduce the voltage concentration on the first turn of the coil.

The repetitive PD extinction voltage (RPDEV) is determined by reducing the voltage amplitude of surge voltages, until PDs occur irregularly. The averages and the standard deviations of the RPDEV are similar to the RPDIV and differ just between 3 % and 4 %, which is near the step size of 50 V, what makes it sufficient to measure only the RPDIV. The discussed hysteresis effect in standard [7] and its safety factor provides an overestimation of lasting PDs for switched voltages. In the final construction, the windings of electrical machines are typically impregnated with resin, what suppresses surface discharges on the enameled wire. The mass loss of up to 30 % of the resin during the lifetime must be considered. This leads to an increase of probability of void discharges, which can be the reason for treeing. Thus, this variant shows a worst-case estimation of the maximum voltage to avoid partial discharges and electrical ageing of the winding insulation.

TABLE III. WEIBULL PARAMETERS FOR SINUSOIDAL VOLTAGES.

| **Nominal diameter in mm** | **PDIV** $\mu$ / $\sigma$ **in V** | **PDEV** $\mu$ / $\sigma$ **in V** | $\frac{\text{PDIV} - \text{PDEV}}{\text{PDIV}}$ **in %** |
|---|---|---|---|
| 0.50 | 1326 | 1093 | 17.6 |
| | 120 | 137 | |
| 1.06 | 1440 | 1179 | 18.2 |
| | 139 | 118 | |
| 1.60 | 1395 | 1213 | 13.0 |
| | 107 | 163 | |

TABLE IV. WEIBULL PARAMETERS FOR SWITCHED VOLTAGES.

| **Nominal diameter in mm** | **RPDIV** $\mu$ / $\sigma$ **in V** | **RPDEV** $\mu$ / $\sigma$ **in V** | $\frac{\text{RPDIV} - \text{RPDEV}}{\text{RPDIV}}$ **in %** |
|---|---|---|---|
| 0.50 | 2137 | 2066 | 3.3 |
| | 358 | 363 | |
| 1.06 | 1853 | 1775 | 4.2 |
| | 413 | 413 | |
| 1.60 | 1723 | 1654 | 4.0 |
| | 389 | 390 | |

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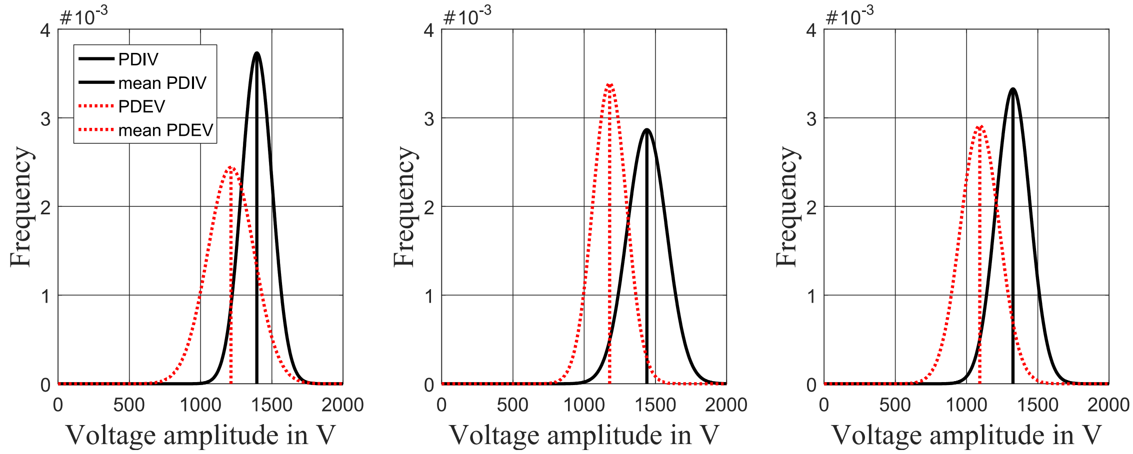
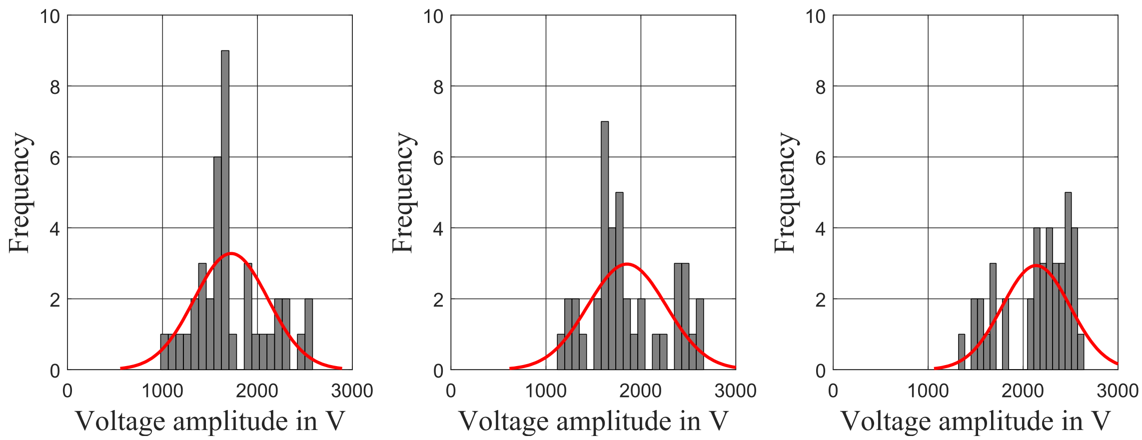



a) Partial Discharge Inception and Extinction Voltage (PDIV and PDEV) for a sinusoidal voltage.




b) Repetetive Partial Discharge Inception Voltage (RPDIV) for a unipolar voltage impulse.

Fig. 6. Measured Partial Discharges Inception Voltages between twisted pairs of enameled wires with different nominal diameter (left 1.6 mm, middle 1.06 mm, right 0.50 mm).

## V. Conclusions

This digest presents a methodology to identify the critical points of electrical fields, which can deteriorate the insulation of the entire winding system. The general approach of the methodology is to first calculate the maximum magnitudes of the voltage in the drive system and then to identify the inhomogeneous field distributions for different electrode arrangements representing the insulation. This methodology allows in combination with FE-simulations to identify the most crucial electrical fields of the entire insulation system. It has been shown that it is not sufficient to design and improve the insulation system only with simulations of the electrical loads. A quantitively relationship between simulated electrical fields and the probability of partial discharges cannot be found using different manufacturing forces of enameled wires with different nominal diameters.

The influence of production-related parameters such as pulling force during winding of the test set-up specimen or pressing of winding head strongly influences the probability of partial discharges and must be studied in further research.

The voltage shape has an extensive influence on the probabilistic parameters of partial discharges. In the case of partial discharges inception voltage with unipolar voltage surge the standard deviation is relatively to sinusoidal test voltages enormous. This results into limited voltages between winding turns to prevent the insulation of electrical ageing due to partial discharges.

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