Study on Temperature Dependence of Partial Discharge in Low Voltage Traction Drives

F.Pauli, N.Driendl, K. Hameyer

Abstract – **Due to rising DC-Voltages and voltage slew rates (du/dt) partial discharge (PD) phenomena move into the focus for low voltage traction drives. State of the art systems are designed to be PD-free at any point of operation. Elevated temperatures yield decreased partial discharge inception voltages (PDIV). In the design process, this is considered by measurements at rated operation employing safety factors which predict the PDIV at higher temperatures. Traction drives in electric vehicles have an increasing electrical and thermal utilization to increase power density. To allow for a more precise design process for these machines, studies on the temperature dependence of PDIV are performed and discussed in this paper.**

***Index Terms*—Discharges, Partial discharges, Rotating machines**

I. Nomenclature

A, B	Parameters for *Townsend* equation
T, T_0, T_t	Temperature (at nominal and testing conditions)
U_a	Stationary voltage
U_p	Peak voltage
U_B	Minimum voltage for discharge processes
V	Volume
d	Distance
du/dt	Voltage slew rate
k_B	*Boltzmann* constant
n	Number of particles
p	Pressure
p_t	Equivalent pressure (Dunbar correction)
t_r	Rise time
γ	secondary electron emission coefficient

II. Introduction

Increasing voltage slew rates (du/dt), switching frequencies and DC-link voltages bring partial discharge into focus for traction machines. Recent research activities investigate the dependence of PD-activity on the parameters of square wave voltages in low voltage drives [1]-[3]. The insulation systems of such machines are designed to be PD- free at any operating point. Qualifying an insulation system as PD-free is usually done by measuring the partial discharge inception voltage (PDIV) at room temperature and applying safety factors that take the maximum operating temperature, ageing and the difference between PDIV and partial discharge extinction voltage (PDEV) into account [4]. These safety factors are based on experience.

Recently, in traction applications, DC-link voltages are increasing [5]. This leads to the usage of new insulation materials such as PEEK or innovative polyamide-imide insulation materials with decreased permittivities [6]. Due to the introduction of such new materials and the trend towards thermally highly utilized machines, an experience-based factor might no longer meet the needs of the designer of the insulation system.

Therefore, in this paper a measurement setup to identify the temperature dependence of PDIV and PDEV is presented. For an exemplary enameled wire, measurements are carried out.

In [7] the discharge inception voltage between two spherical electrodes made of stainless steel is measured for different temperatures. The obtained measuring data is compared to the theoretical *Paschen* curve, corrected with a factor for the temperature influence according to [8] and [9]. Here, a decreased inception voltage is obtained for increasing temperatures.

The temperature dependence of the permittivity of insulation material is studied in [10] for ethylene propylene rubber. For frequencies above $1\,kHz$ there is only little temperature influence therefore in this paper the permittivity is regarded as constant.

For oil paper insulation systems that are applied in high voltage transformers the temperature dependence is investigated in [11]. In this case, an increase in temperature also leads to a decrease of PDIV. In [12] a high-voltage rotating machine is regarded and it is shown, that outer PD-activity is higher for increased temperature while the PD-activity in air enclosures is lower.

In this paper, the interturn insulation of low voltage traction drives is regarded. For this purpose, twisted pairs of enameled wires without any impregnation are studied. Polyamide-imide (PAI) and polyester-imide (PESI) are widely used materials for such insulation systems. In [13] the PDIV is measured for a setup of a rod electrode and polyimide film, a material with similar properties to PAI and PESI, showing also a decrease of PDIV for increasing temperatures. However, only temperatures between 25 °C and 80 °C are regarded, while winding head temperatures of modern traction machines can exceed 200 °C in short term operating points.

The PDIV depends on the voltage slew rate (du/dt) [14]. Therefore, in this paper the temperature dependence of PDIV is studied using an SiC-pulse generator, that provides high slew rates as they occur in SiC-inverter-driven machines.

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III. Temperature Dependence of Discharge Processes

Partial discharge is a gas discharge process, which only bridges a part of the insulation. Contrary to that, a breakdown occurs between two conductors. In both processes, the necessary charge carriers are produced by the collision of electrons with gas molecules, which are then ionized and produce additional electrons. This process however only takes place, if the electrons gain sufficient energy, while they are accelerated in the electric field between to electrodes. If the electric field is too low, the electron will not gain enough energy to ionize a molecule when a collision takes place. Therefore, a high density of molecules lowers the likelihood of discharge processes. Also, if the electrodes are close to each other, such that the electron will hit the anode before ionizing molecules no discharge will happen.

To calculate the minimum voltage that is needed to initiate a discharge process between two electrodes the *Townsend* equation (eq. (1)) is used. Here, U_B is the breakdown voltage, p is the gas-pressure, and d is the distance between the electrodes. A and B are gas-specific parameters and γ depends on the combination of cathode material and gas.

$$U_B = \frac{B \cdot p \cdot d}{\ln(A \cdot p \cdot d) - \ln\left(1 - \frac{1}{\gamma}\right)} \tag{1}$$

In this equation, no temperature dependence is displayed. Experience show however a significant temperature dependence of PD-processes [11]-[14]. To consider this in [8] and [9] two different correction methodologies are introduced. For *Peek* correction, the breakdown voltage is scaled according to eq. (2). T_0 is the temperature where the *Townsend* equation is parametrized (in this paper 293 K) and T is the actual operating temperature.

$$U_B(T) = U_B(T_0) \cdot \frac{T_0}{T} \tag{2}$$

For the *Dunbar* correction, an equivalent pressure p_t is calculated (eq. (3)). The pressure p in eq. (1) is then substituted by p_t.

$$p_t = p \cdot \frac{T_0}{T_t} \tag{3}$$

The calculation of p_t is based on the consideration, that according to eq. (4) the number of molecules n inside a Volume V of an ideal gas at a given pressure p changes reciprocal to the absolute temperature T.

$$p \cdot V = n \cdot k_B \cdot T \tag{4}$$

In Fig. 1 the *Paschen* curve for a material combination of PAI and air is displayed for room temperature and for a temperature of $200\,°C$. The temperature index of the enameled wire which is investigated later. The pressure that is used to calculate the *Paschen* curve is 1013 hPa. For the *Peek* correction the minimum voltage in the *Paschen* curve changes, while it is only shifted to higher distances for the *Dunbar* correction (cp. Fig 1). For distances of more than 0.5 mm *Peek* and *Dunbar* correction yield the similar breakdown voltages.

The temperature influence on the cathode material is, however, not regarded in the *Dunbar* correction. In this paper, the interturn insulation is studied by applying a pulsed voltage to twisted pair specimen, which are produced according to [15]. The electric field distribution can be regarded using a simplified 2D-setup as displayed in Fig. 2. The enamels of the wires touch in the region where the electric field is the highest. This point is to the left of the *Paschen* minimum in Fig. 1. Partial discharge will therefore occur where the conductors are further apart.

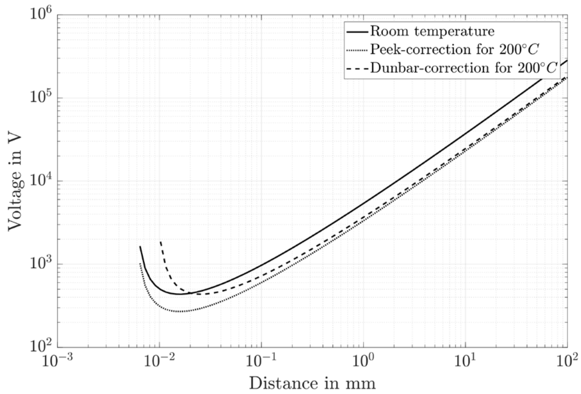

Fig. 1: *Paschen* curve for room temperature, and a temperature of 200 °C with *Dunbar* and *Peek*- correction at an air pressure of 1013 hPa.

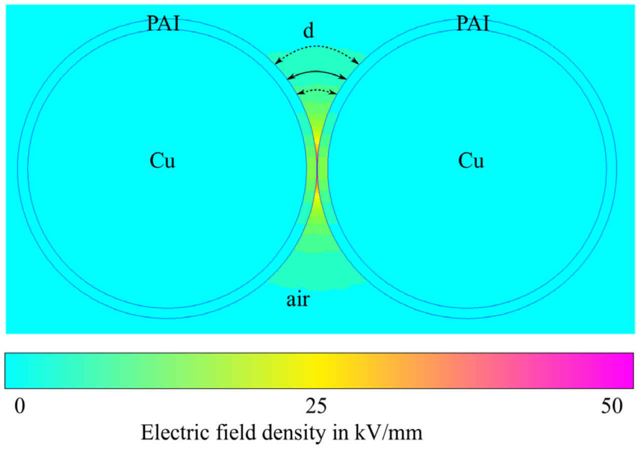

Fig. 2: Electric field density in a 2-D-setup of two enameled wires with a voltage of 1000 V between the conductors.

The minimum voltage at which PD is possible for the setup in Fig. 2 can be calculated by expressing the field density as a function of the distance d. This function depends on the voltage between the two conductors. The *Paschen* curve can also be expressed in terms of electrical field over the electrode distance. The voltage where the *Paschen* curve and the field strength as a function of distance meet, but do not intersect is the calculated discharge inception voltage (Fig. 3).

Depending on the temperature correction the *Paschen* curve and therefore the calculated discharge inception voltage will change. This variation of the *Paschen* curve and the influence on the determined PDIVs is schematically depicted in Fig. 4

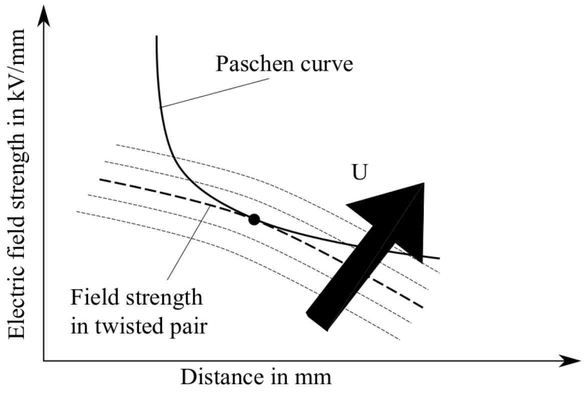

Fig. 3: Determination of discharge inception voltage.

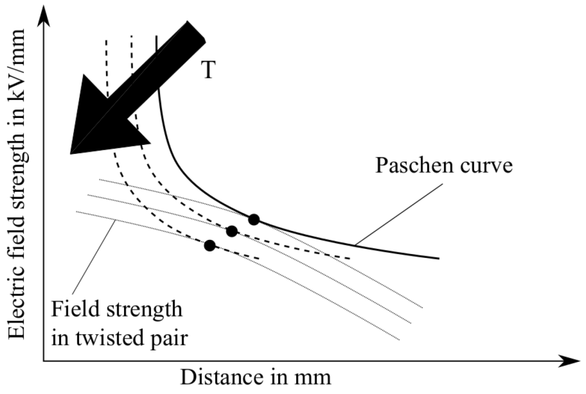

Fig. 4: Influence of increasing Temperatures on the *Paschen* curve and the calculated PDIVs according to *Dunbar* correction.

IV. Measurement Setup

In this paper, the PDIV of twisted pairs is measured at different temperatures. For this purpose, the setup that is presented in Fig. 6 and Fig. 7 is employed. An SiC-generator which provides a voltage waveform with a high slew rate (du/dt) is used as a voltage source. Due to the high temperatures inside the oven, the SiC-generator is placed outside. Thus, a cable with a length of 1 m is necessary to connect the specimen and the generator. The voltage source provides a bipolar pulsed voltage that resembles the output voltage of an inverter and can be characterized by the switching frequency and the following quantities depicted in Fig. 5:

- Stationary voltage (U_a)
- Voltage slew rate (du/dt)
- Peak voltage (U_p)
- Rise time (t_r)

The overshoot factor OF is calculated according to eq. (5), where ΔU is the difference of the voltage between the point of time where the switching process is initated and the peak voltage U_p (cp. Fig. 5)

$$OF = \Delta U / 2U_a \tag{5}$$

Employing the IEM-HV-SiC-generator, which is introduced in [1] the switching frequency f_{sw}, the voltage slew rate du/dt and the voltage U_a can be adjusted independently. The overshoot factor depends on the cable length between the generator's terminals and the specimen as well as on the slew rate (du/dt).

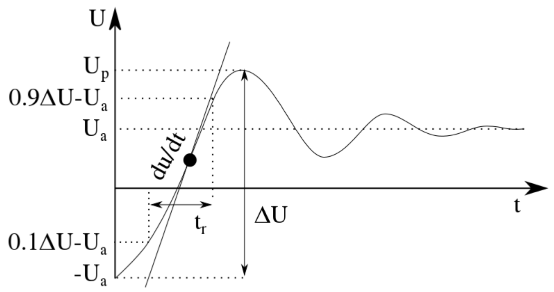

Fig. 5: Nomenclature for pulsed voltages.

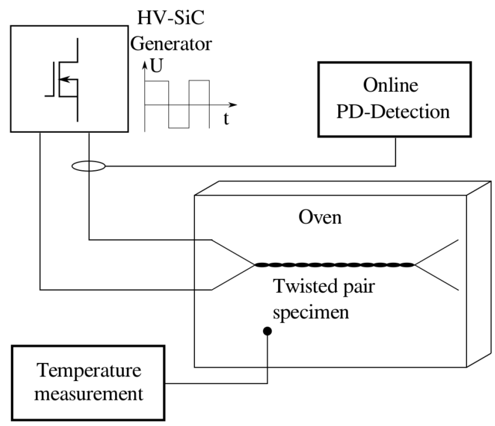

Fig. 6: Setup for PDIV-Measurment.

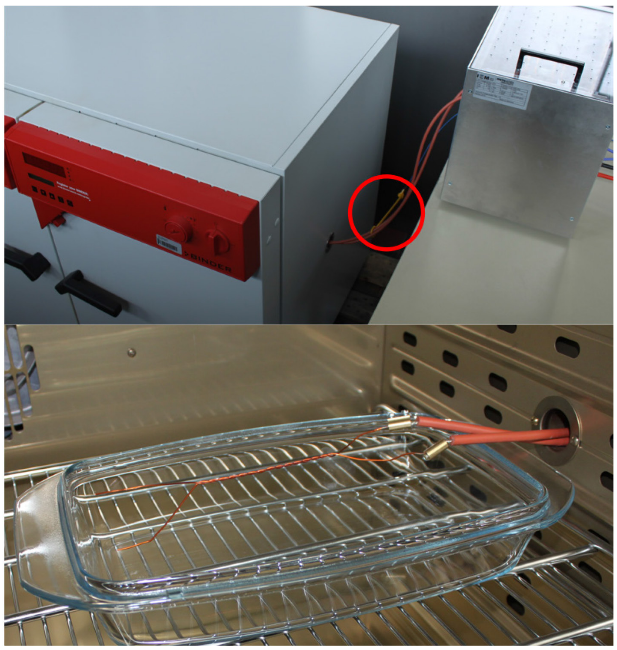

Fig. 7: Setup for PDIV-Measurement; top, left to right: Oven, magnet field antenna (circled) and HV-SiC generator; bottom: Twisted pair specimen inside the oven.

TABLE I
PARAMETERS OF THE ENAMELED WIRE.

Parameters	Value
Manufacturer	Dahréntråd
Product name	Damid 200
Nominal diameter	1.0 mm
Temperature index	200 °C
Insulation grade	2

The specimens used in this paper are twisted pairs made of the wire which is specified in in TABLE I.

The enameled wire is subjected to temperatures between room temperature (20 °C) and the temperature index of the wire (200 °C). For this purpose, the specimens are placed inside an electrically isolating containment, which is placed inside an oven of controlled temperature. During the measurement, a thermocouple is placed inside the containment where the specimen is located. The error between actual and set temperature is within $\pm$ 2.5°C for each specimen.

Once PDIV and PDEV for one specimen are measured at room temperature, the temperature is set to 50 °C. When the desired temperature is reached, PDIV and PDEV are measured for the same specimen. This procedure is continued until 200 °C are reached.

The generator switching frequency is $20\ kHz$. The voltage waveform is displayed in Fig. 8. In order to contact the specimen inside the oven, a relatively long cable with a length of 1 m is necessary. This leads to an overshoot factor of 1.25. All operating points where PDIV and PDEV are measured, are collected in TABLE II.

TABLE II
PARAMETERS OF THE BIPOLAR PULSE VOLTAGE.

Parameter	Value
Temperatures T	20, 50, 100, 150, 200 °C
Switching frequency f_{sw}	20 kHz
Voltage slew rate du/dt	45 kV/µs
Overshoot factor OF	1.25

To remove statistical uncertainty, for each operating point five specimen are measured. In order to measure PDIV the voltage for each specimen is turned on at $600\ V$ and then increased by $2\ V/s$ until PD is detected. The measured PDIVs in this paper always refer to the stationary voltage U_a.

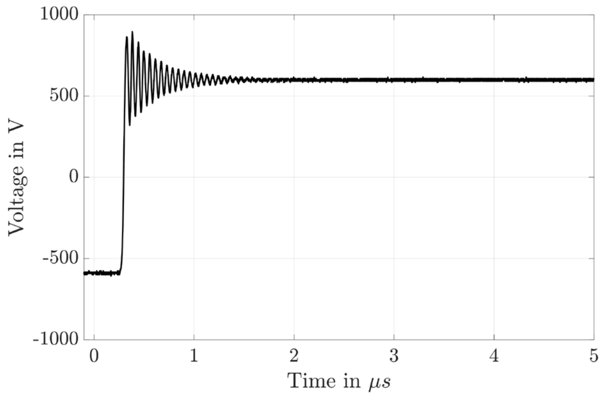

Fig. 8: Measured voltage at specimen terminals

V. MEASUREMENT RESULT

Regarding the *Townsend* equation (eq. (1)), the parameters A and B and break down characteristics for air are well known from literature [16] –[18]. The second *Townsend* coefficient γ is also well known for combinations of metallic electrodes and different gases, however for a combination of polyamide imide and air only few studies have been carried out (e.g. [19]). Due to uncertainty, in this paper γ is adapted in such a way, that it matches the obtained results from the PDIV measurement at room temperature (998.8 V). The parameters used for the *Townsend* equation at room temperature are given in TABLE III.

TABLE III
PARAMETERS FOR THE PASCHEN CURVE.

Parameter	Value
A	112.5 1/kPa cm
B	2737.5 V/kPa cm
γ	1.148e-4

Using this parametrization, the minimum voltage where PD can occur is calculated as a function of temperature using *Peek* and *Dunbar* correction. The resulting curve and the measured PDIVs are plotted in Fig. 9.

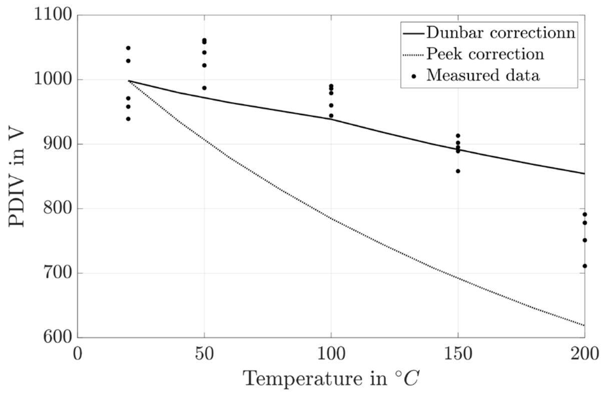

Fig. 9: Measured and calculated PDIV as a function of temperature.

The *Peek* correction yields significantly lower PDIVs than the measured data, while the *Dunbar* correction can be used for temperatures of up to 150 °C. For higher temperatures, the measured PDIVs are significantly lower than the estimate. In [4] the difference of PDIV at room temperature and the operating temperature is calculated by using an empirical factor of 1.3, which in this case – depending on the operating temperature – also underestimates the PDIV eq. (5).

$$PDIV(T) = \frac{PDIV_0}{1.3} \tag{5}$$

In eq. (1) the material parameters of the cathode is solely addressed by the parameter γ. The *Dunbar* correction offers a physical approach but only takes temperature related effects of the air between the electrodes into account. Therefore, now the temperature dependence of γ is regarded. For this purpose, the field solution of the twisted pair is taken for the measured PDIV at a given temperature. Then, *Dunbar*-correction is applied and the parameter γ is adjusted as previously for the initial determination of γ. This process is displayed in Fig. 10. The permittivity of the insulation material is kept constant.

In Fig. 11 the resulting values for γ are depicted. For temperatures of up to 150°C the obtained values are in the same range. $\gamma(200°C)$ is however significantly higher. The value for 20°C is also higher than for temperatures between 50°C and 150°C. However, contrary to the other operation points the wire has never been subjected to high temperatures or partial discharge in this operating point.

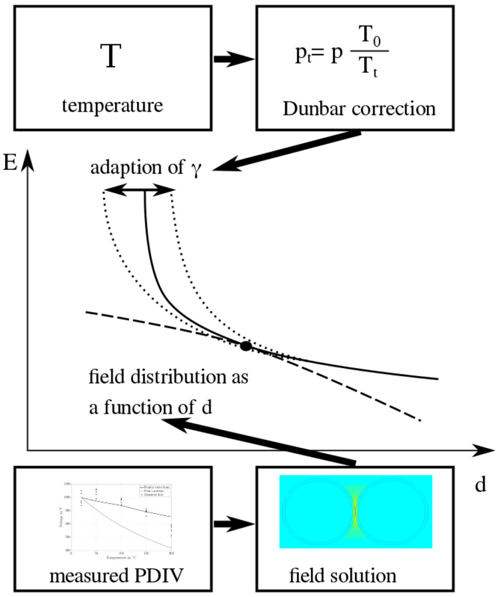

Fig. 10: Process to determine the value of γ as a function of temperature.

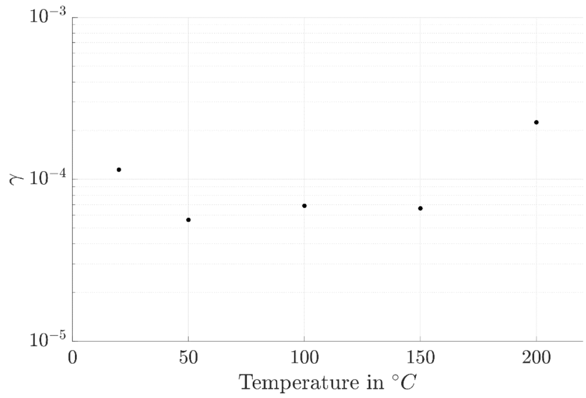

Fig. 11: Calculated *Townsend* coefficient as a function of temperature.

In the design process of the insulation system not only the PDIV but also the PDEV needs to be regarded. In a winding system that is operated at voltages below its PDEV a single partial discharge will hardly cause any damage. Such a PD can be caused by transient voltages or a nearby lighting strike. However, if the winding is operated between PDEV and PDIV, such an event can lead to partial discharge that will last until the supply voltage is switched off. Under such circumstances, the remaining lifetime of the insulation is drastically reduced [1]. Therefore, low voltage drives should always be operated below their PDEV. In [4] this is ensured by multiplying the design voltage of the system in the qualification process with a safety factor of 1.25 and comparing it to the measured PDIV. This is equivalent to calculating the PDEV as:

$$PDEV = \frac{PDIV}{1.25} \tag{6}$$

The measured and the calculated PDEVs are displayed in Fig. 12. Just like the PDIV the measured PDEV decreases as the Temperature increases. However, for a temperature of 200 °C the PDEV is increased for all 5 specimen that have been tested. This can be explained by the decreasing amount of molecules inside the gap between the conductors for higher temperatures. Below a certain value, an accelerated electron is more likely to hit directly the anode than to ionize another molecule and cause PD. This situation would correspond to the left side of the *Paschen* minimum depicted in Fig. 1. For temperatures below 150°C the measured PDEV is lower than the PDIV corrected by the safety factor from [4]. For the enamel that is studied in this paper a bigger safety factor is necessary to ensure a PDIV-free operation.

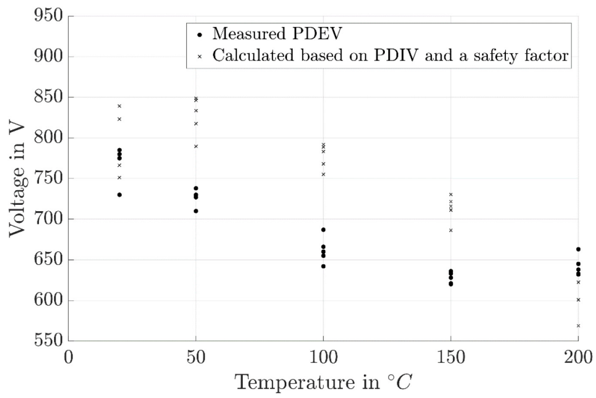

Fig. 12: Measured and calculated PDEV based on the safety factor from IEC 60034-18-41 [4] as a function of Temperature.

Considering the difference between PDIV and PDIV using a single safety factor is also problematic regarding the variation of the voltage waveform. In Fig. 13 PDIV and PDEV of 10 are measured at room temperature for different frequencies. The switching frequency is varied between 10 kHz and 40 kHz. While the PDIV is not significantly varying when changing the frequency, the PDEV decreases, when increasing the frequency.

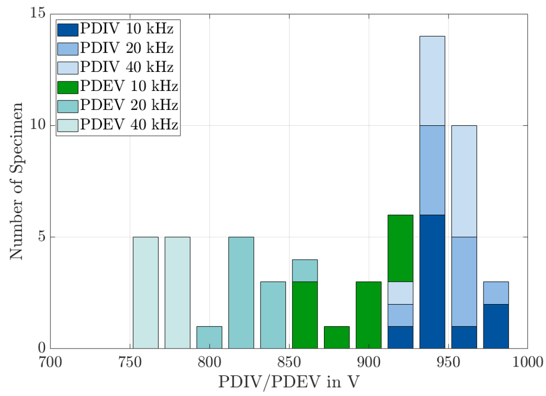

Fig. 13: PDIV and PDEV of 10 twisted pair specimen at different switching frequencies.

VI. CONCLUSIONS

In this paper the temperature dependence of PDEV and PDIV for twisted pairs of enameled wires is studied. IEC 60034-18-41 [4] which is used to qualify insulation systems uses empirically based factors to takes the temperature dependence and the difference between PDEV and PDIV into consideration. These safety factors are not sufficiently accurate to be used on the entire operating range of the machine. Particularly the safety factor for the difference between PDIV and PDEV may overestimate the PDEV for some operating points. This can lead to the design of insufficient reliable insulation systems. More detailed models are the *Peek*- or *Dunbar* correction of the *Paschen* curve. The measurements in this paper show however, that the *Peek* correction underestimates the PDIV, while the *Dunbar* correction offers a more accurate estimate for temperatures of up to 150 °C. For higher temperatures, the PDIV is overestimated, which can again lead to a poorly designed insulation system. More precise data concerning the second *Paschen* coefficient may offer the possibility to model the PDIV more precisely. In addition, it is shown, that PDEV does not solely depend on the temperature but also on the voltage waveform. At higher frequencies the PDEV is decreased. As PDIV and PDEV are highly load dependent, measurements which consider thermal and electrical load will lead to more accurately designed insulation systems than using state of the art standards with safety factors.

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VIII. BIOGRAPHIES

Florian Pauli received the M.Sc. degree in electrical engineering from RWTH Aachen University, Germany, in April 2017. He has been working as a research associate at the Institute of Electrical Machines since May 2017. His research interests include iron loss computations, thermal behavior, overload capability, lifetime models and the characterization of insulation systems of electrical machines.

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His research interest focuses on all aspects of the design, control and manufacturing of electrical machines and the associated numerical simulation. The characterization and modeling of hard- and soft-magnetic materials is another focus of his work. He has authored/coauthored more than 350 journal publications, more than 700 international conference publications and four books. His research interests include numerical field computation and optimization, the design and control of electrical machines, in particular, permanent-magnet excited machines, induction machines.
Dr. Hameyer is a member of the German VDE, a senior member of IEEE and a Fellow of the Institution of Engineering and Technology, U.K