

High dv/dt Testing of Coil Winding Insulation Systems for Wide-Bandgap Applications

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Abstract—To increase efficiency and reduce material consumption, the increased use of wide-bandgap (WBG) power semiconductor devices becomes indispensable. However, challenges such as the accelerated aging of insulation materials have so far prevented exploiting the full potential of this technology. This paper provides an overview of experiments that can be performed to test insulation systems for their resilience with respect to fast switching transients. To this end, capacitive and inductive specimens are considered. Firstly, the test bench is briefly introduced. Secondly, measurements are performed with standardized twisted pair of enameled wire specimens. The lifetimes at two different voltage slopes are compared, the effect of a consistent discharge at steep voltage slopes is analyzed and the influence of a partial discharge (PD) resistant additive in the enamel is considered. Then, single-tooth coil windings with and without a PD-resistant additive in the enamel are investigated and the influence of an optimized winding configuration demonstrated.

Index Terms—Wide bandgap semiconductor power devices, WBG, Insulation, Breakdown, high dv/dt, fast switching transients, SiC, DBD

I. INTRODUCTION

Wide-bandgap (WBG) power semiconductor devices offer many advantages. One key advantage is the fast switching behavior, which leads to lower switching losses and, in turn, allows higher switching frequencies. Thus, the power density of power electronic systems can be increased and the required material is reduced [1]–[4]. However, the fast switching transients of WBG devices have led to concerns regarding the impact of the accompanied steep voltage slopes on the performance and reliability of the power electronic systems, since they can lead to accelerated aging and a premature failure of insulation systems [5]–[11]. Insulation systems are a critical component in power electronics and electrical drives, and their failure can lead to significant safety issues. Therefore, it is crucial to investigate the impact of the fast switching transients to be able to develop countermeasures accordingly and finally, fully exploit the potential of WBG power semiconductor devices. To this end, the test bench that is introduced in [12] is used to perform experimental investigations with different specimens. Firstly, twisted pairs of enameled wires are investigated by conducting end-of-life tests, considering different dv/dt (voltage slope) and insulation systems. Subsequently, single-tooth coil windings of an twelve-phase electrical machine are considered. The lifetime with and without a partial discharge (PD)-resistant additive in

the enamel of the wires and the PD behavior are compared. Furthermore, the influence of the winding configuration on the parasitic behavior of a coil winding is demonstrated. From the results, initial conclusions are deduced regarding strategies to enhance the longevity of insulation systems for coil windings in WBG applications.

II. TEST BENCH AND EXPERIMENTAL SETUP

To investigate the influence of the voltage slope on the aging behavior of insulation systems, a voltage-slope generator, based on SiC-MOSFETs, is developed and introduced in [13]. This voltage-slope generator allows to set an adjustable and defined dv/dt of up to 116 V/ns, without changing the hardware setup. Therefore, it features parallel push-pull branches in the gate driver which is a commonly used concept to influence the switching behavior for reducing switching losses and electromagnetic interferences [14]–[19]. It is capable of unipolar and bipolar voltage waveforms and dc-link voltages of up to 800 V. In Fig. 1, the range of voltage slopes is demonstrated. Even for a high dv/dt , the voltage overshoot is relatively low at 6.9 %. A low voltage overshoot is advantageous, as high voltage

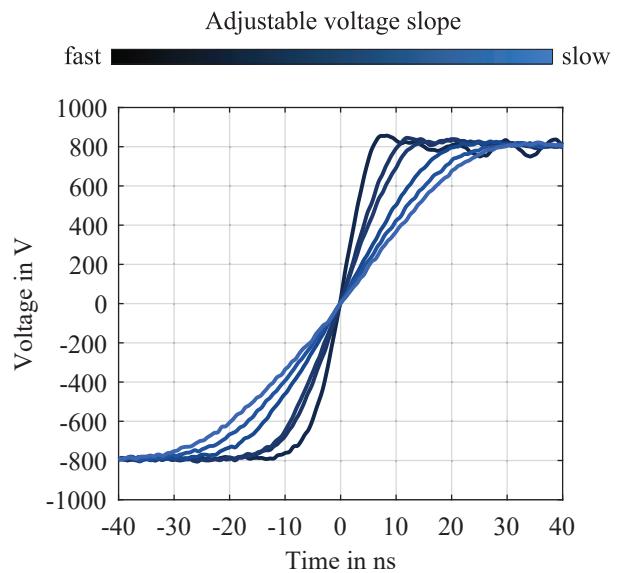


Figure 1. Output voltage transients with different steep voltage slopes of the voltage-slope generator [13].

slopes are often accompanied by increased voltage overshoots. Both factors can contribute to accelerated aging effects. Thus, a reduced voltage overshoot, even for steep voltage slopes, serves to mitigate such cross-coupling effects.

The voltage-slope generator is integrated into a test bench which is described in detail in [12]. The test chamber of this test bench is electromagnetically shielded to prevent interferences from the environment. The measurement equipment used to record electrical and electromagnetic parameters during the end-of-lifetime tests features high bandwidths. Overall, this test bench allows insulation tests for WBG applications under defined conditions. A simplified schematic diagram of the experimental setup with the equipment relevant for this paper is shown in Fig. 2. The voltage is measured with a 800 MHz *TIVH08* differential voltage probe by *Tektronix* [20] and is connected directly to the specimen. The current probe is of type *TCP0030A* by *Tektronix* and features a bandwidth of 120 MHz [21]. It can measure conductive currents and displacement currents. However, it is not suitable for detecting PDs. Instead, the PDs are detected via an antenna that is connected to a band-pass filter of 290 MHz – 3 GHz.

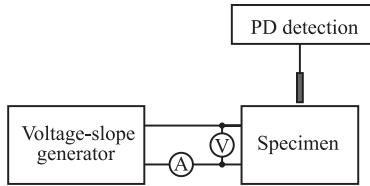


Figure 2. Schematic diagram of the experimental setup.

For the experiments, two different types of specimens are used. First, standardized twisted pairs of enameled wires are considered and preliminary tests are performed. Then, coil windings of a single stator tooth from a twelve-phase machine with two different enameled wires are investigated. Furthermore, the influence of an optimized winding configuration is examined. Using coil windings as specimens has the advantage that the geometry is closer to the application. The advantages are that influencing factors, such as the iron core effect, resonances and damping due to longer conductors, electric fields between conductors that are not twisted and reflections due to the higher impedance of the load. However, coil-winding specimens are more expensive than twisted-pair specimens. Therefore, preliminary experiments are often performed with twisted-pair specimens to reduce the costs. In the following, both specimen types are described in detail.

III. TWISTED PAIR OF ENAMELED WIRES

Insulation tests of enameled wires are often performed in the configuration of a twisted-pair specimen, as exemplary shown in Fig. 3. The number of twists and the load of the twisting depends on the diameter of the wire and is defined in the standard IEC 60851-5 [22]. These specimens emulate the worst case scenario of a winding configuration where the first and the last winding are adjacent, and offer a cost

efficient method to investigate enameled wires. Due to the standardized method of construction, these specimens provide a good basis for comparison with other research work. In the following, enameled wires with a diameter of 0.85 mm are used. The enamel is based on theic-modified polyesterimide and a polyamide-imide overcoat.



Figure 3. Picture of standardized twisted pair specimen [12].

A. Lifetime Comparison Considering Different Voltage Slopes

First, end-of-life tests are performed at different voltage slopes of a bipolar rectangular voltage waveform. The dc-link voltage is set to 800 V and the switching frequency to 500 kHz. The first batch of twisted-pair specimens is excited with 110 V/ns and the second batch with 50 V/ns. These are not common voltage slopes for IGBTs, however, they represent the trend when using WBG power semiconductor devices. The resulting lifetime of the specimens at the respective voltage-slope excitation is shown in Fig. 4 and is based on the results in [12]. However, for this experiment, the number of specimens has been increased. It can be seen that the median lifetime of the specimens excited with 50 V/ns is with 157 s significantly higher than the median lifetime of the specimens excited with 110 V/ns, which features 15 s, while the lifetime is relatively short for both voltage slopes. This shows that the voltage slope can have a severe impact on the lifetime of the insulation systems of enameled wires.

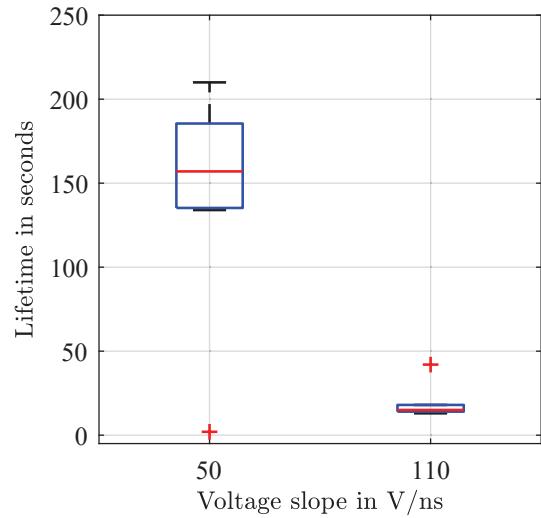


Figure 4. Lifetime comparison for twisted pair specimens excited with 50 V/ns and 110 V/ns.

B. Dielectric Barrier Discharge

Especially when excited with 110 V/ns , a persistent discharge is visible. To specify the type of discharge, the cross section of a twisted pair specimen is illustrated in Fig. 5. The electrode configuration consists of two copper wires, surrounded by a dielectric, the enamel. Thus, this discharge is defined as dielectric-barrier discharge (DBD) [23].

Figure 6 shows the equivalent circuit of this electrode configuration. The voltage v_{sw} is applied between the two copper wires. The dielectric of the enamel is modeled as a capacitance C_d . In the twists, there is also air that needs to be considered. On the one hand, the air gap between the two enameled copper wires can be described as an additional capacitance C_{gap} . On the other hand, the resistance of the air R_{air} needs to be considered as well. In the absence of DBD, R_{air} is sufficiently large to be neglected, meaning that the total current i_{total} is equal to the displacement current i_{disp} . However, when DBD occurs, the conductivity of the air increases, and thus, the resistance R_{air} decreases. Therefore, R_{air} can no longer be neglected and the total current i_{total} is now the sum of the displacement current i_{disp} and the conduction current i_{cond} .

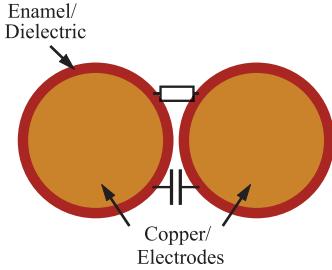


Figure 5. Electrode configuration of a twisted pair specimen.

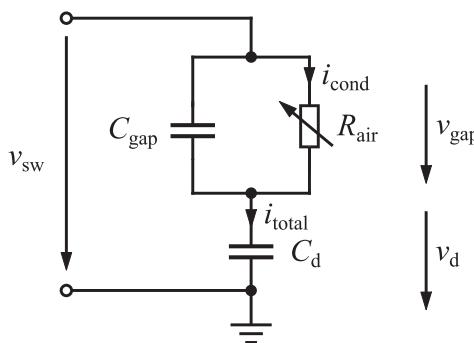


Figure 6. Equivalent circuit of electrode configuration of twisted pair specimens [12].

C. Lifetime Comparison Considering Different Types of Enamelled Wires

The enameled wire examined in Sec. III-A (EW1) is compared with a second type of enameled wire. The base coating of this enameled wire is the same as the first one, but it additionally contains a PD-resistant additive (EW2). The key information of the comparison is summarized in Tab. I.

Table I
TYPES OF ENAMELED WIRES

Designation	Diameter	PD resistant
EW1	0.85 mm	no
EW2	0.85 mm	yes

In [12], it is shown that at 110 V/ns , the lifetime of EW2 is even shorter compared to EW1. Since at a voltage slope of 110 V/ns DBD occurs and the lifetime is therefore deficient, the PD behavior in the absence of DBD needs to be examined. Therefore, for the lifetime comparison between these two enameled wire types, a voltage slope of 50 V/ns is considered. The data for this experiment is based on the results of the experiments in [12], but here, the number of specimens has been increased. Figure 7 shows that the median lifetime of the enameled wire with the PD-resistant additive (EW2) of 1124 s is significantly increased compared to EW1. However, it also features a higher variation in results.

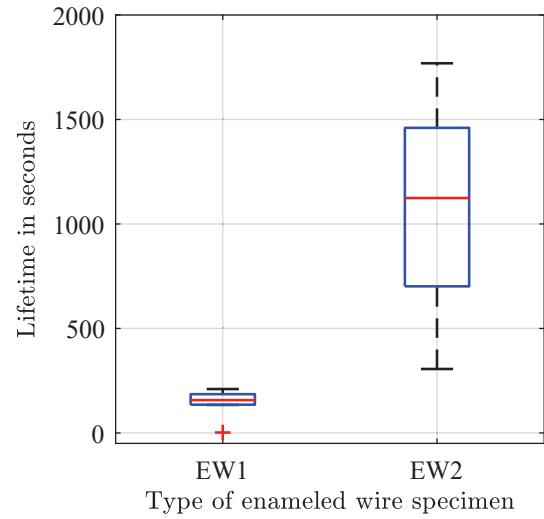


Figure 7. Lifetime comparison of twisted pair enameled wire specimens without (EW1) and with (EW2) a PD-resistant additive.

IV. SINGLE TOOTH WINDINGS

Twisted pair specimens emulate the worst case scenario in a winding configuration, representing the case in which the first and the last winding are placed directly next to each other. In this case, the insulation between the two

windings experience the maximum voltage drop. However, especially when considering concentrated coil windings, the configuration of the winding allows a specific placement of each winding in a layer. Thus, the adjacency of the first and the last winding can be avoided. In this paper, single teeth of a twelve-phase machine with concentrated windings are considered, as they are described in [24] and [25]. For the winding configuration, a classical approach is used, where the first winding starts within the inner layer and the last winding finishes at the outer layer. A picture of such a single-tooth coil winding is shown in Fig. 8.



Figure 8. Single-tooth coil winding of a twelve-phase machine.

A. Definition and Settings of the Voltage Slope

Attaching a load to the voltage-slope generator influences the switching behavior. It is shown in [12] that the influence on the voltage slope of the capacitance of a twisted pair of enameled wire is negligible. For inductive loads such as single-tooth windings, however, the influence on the switching behavior is substantial and cannot be neglected, as demonstrated in Fig. 9. Under no-load condition, a steep voltage slope with a low voltage overshoot is achieved. When applying a single tooth coil winding as a load, not only the voltage overshoot increases, but also the shape of the voltage slope changes significantly.

In the first section of the slope, a slow increase of the voltage can be noticed. Then, at approximately -400 V, the voltage slope clearly increases. Therefore, it is essential to consider the influence of the load when performing tests with defined voltage slopes. Furthermore, the definition of the voltage slope is crucial when investigating its impact. This is demonstrated in Tab. II, where the voltage slopes for different definitions are listed for the no-load scenario and the single-tooth coil winding as load scenario from Fig. 9.

Commonly, the 10 % to 90 % criterion is defined as the voltage slope between the point when the voltage has increased by 10 % until 90 % of the peak voltage. However, the voltage peak varies with the load conditions and, additionally, this definition does not take into account the polarity of the voltage waveform. Therefore, the definition of the voltage slope as described in [12] is used in this work. According to this definition, the 10 % ... 90 % criterion corresponds to the voltage slope between 10 % and 90 % of the dc-link voltage.

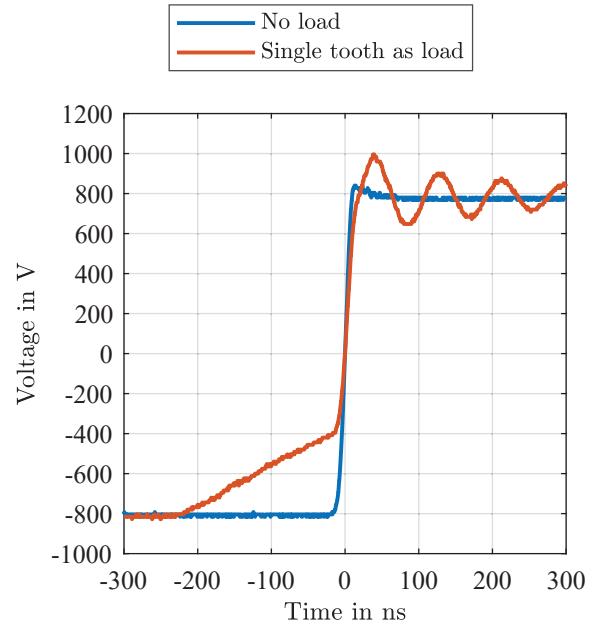


Figure 9. Comparison of the voltage slope under no-load condition and with a single-tooth coil winding as a load.

Table II
RESULTING $\frac{dv}{dt}$ DEPENDING ON THE DEFINITION OF THE VOLTAGE SLOPE WITH RESPECT TO THE DC-LINK VOLTAGE FOR THE NO-LOAD CASE AND A SINGLE TOOTH COIL WINDING AS A LOAD

Voltage slope definition	No load	Single tooth as load
-90 % ... 90 %	80 V/ns	8 V/ns
10 % ... 90 %	88 V/ns	50 V/ns
20 % ... 80 %	94 V/ns	55 V/ns

For the no-load scenario, the voltage slope steepness can vary by 14 V/ns depending on the listed definitions. However, due to the first section of the voltage slope when a single-tooth coil winding is attached as load, the voltage slope varies to a much greater extend, 47 V/ns in the given example, depending on the chosen definition.

For these insulation tests, the steep section of the voltage slope is decisive. Therefore, the first section with the slow increase in voltage is neglected and the definition of the voltage slope steepness between 10 % and 90 % of the dc-link voltage is considered here. Thus, the voltage-slope generator is set to a voltage slope of 88 V/ns under no-load condition, so that with a single-tooth coil winding as a load 50 V/ns are reached, as in the previous tests with the twisted pair specimens.

B. Comparison of Single Teeth with Different Enamelled Wires

In the following, two different types of single-tooth coil windings are compared. For the single-tooth type ST1, the same enameled copper wire as for EW1 is used. The single-tooth type ST2 are coiled with EW2. Thus, the enameled wire

of ST2 has the same base-coating as the enameled wire of ST1, but the enameled wire of ST2 features a PD-resistant additive. Both types are additionally impregnated in insulation resin.

Due to the resonance frequency of the single-tooth specimens at approximately 300 kHz, the switching frequency is reduced to 150 kHz for the following experiments. The number of specimens is limited. Therefore, the results have no statistical relevance. However, a tendency can be observed. For the lifetime comparisons, two ST1 specimens (ST1₁ and ST1₂) and two ST2 specimens (ST2₁ and ST2₂) are considered. The respective lifetimes are listed in Tab. III. The lifetime of the ST1 specimens does not exceed 3 min, whereas the lifetimes of the ST2 specimens is more than 12 min.

Table III
LIFETIME COMPARISON OF THE SINGLE-TOOTH COIL-WINDING SPECIMENS

Individual specimen	Lifetime
ST1 ₁	114 s
ST1 ₂	145 s
ST2 ₁	1565 s
ST2 ₂	779 s

In Fig. 10 and Fig. 11, the average recorded PD events of the ST1 and ST2 specimens are demonstrated. Since the ST2 specimens feature a longer lifetime, and thus, also a longer experiment duration where PDs can occur, the PD incidence is normalized by the lifetime of the respective specimens. Furthermore, the average of both specimens of each specimen type is accumulated. As a result, the average number of PD events per minute, accumulated over the lifetime of both respective specimens is obtained. On the x-axis, the intensity of the PD event is given in p.u., where the base is for all specimens the same.

For low intensities, the average number of PD events per minute is for both specimen types approximately the same. However, for higher intensities, the average number of PD events is higher for the ST2 specimens compared to the ST1 specimens. Moreover, considering the longer lifetime of the ST2 specimens, they experience more PD events in total. This leads to the conclusion that the PD-resistant additive in the enamel of the wire does not necessarily influence the PD behavior, nor reduces the occasions of PD events, however, it does withstand more PD events even with higher intensities. Nevertheless, it is not completely resistant and the lifetime for both specimens of type ST2 is less than 25 min.

Ultimately, it can be deduced that the lifetime of coil windings can be increased by a PD-resistant additive in the enamel of the wire.

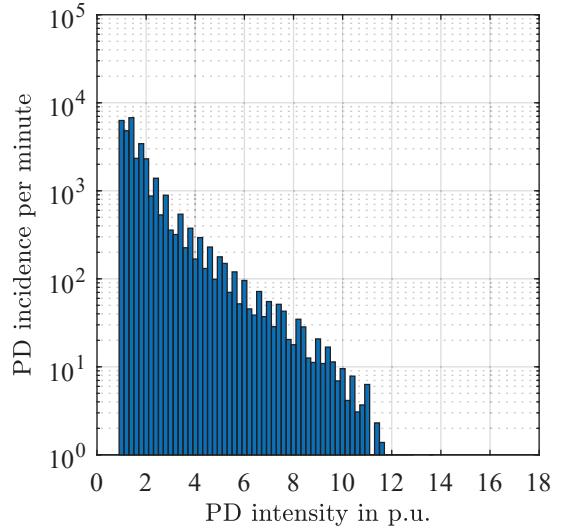


Figure 10. Average PD incidence per minute of the ST1 specimens.

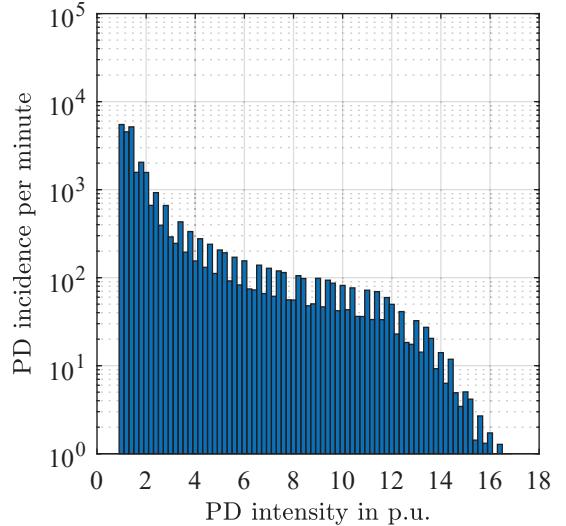


Figure 11. Average PD incidence per minute of the ST2 specimens.

C. Comparison of Single Tooth Coil Windings with Different Winding Configurations

The insulation system is crucial for the lifetime of the component. However, not only the insulation materials itself, but also the winding configuration can have an influence on the lifetime. In this paper, two different winding configurations are considered. The first one has a classical approach, as described above, while the second one is an optimized winding configuration with a center-based approach. Since, as previously shown, the PD-resistant enameled wire (EW2 and ST2) promises a better performance, this type of enameled wire is used for both winding configurations. With the optimized

winding configuration, the coupling capacitance is decreased, and thus, the resonance frequency is increased by approximately 150 kHz, as shown in Fig. 12. The decreased coupling capacitance does not only influence the resonance frequency, but also the current waveforms, as depicted in Fig. 13. The displacement current during the switching event is decreased significantly for the optimized winding configuration compared to the classical winding configuration.

In this work, a lifetime comparison between these two single teeth with different winding configurations is refrained from, since only one specimen is provided in each case. However, it could be observed that the PD incidence is lower for the optimized winding configuration and the lifetime appears to be significantly longer.

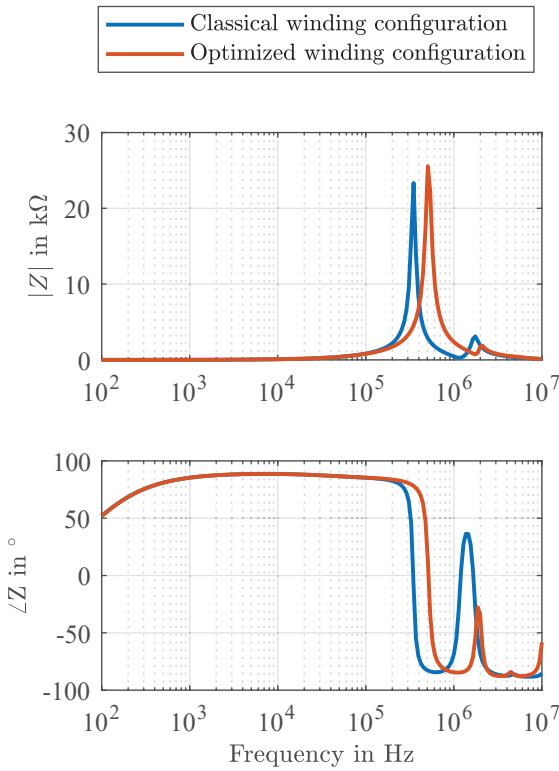


Figure 12. The impedance of the single tooth with the classical winding configuration and the one with the optimized winding configuration by magnitude and phase.

V. CONCLUSIONS AND OUTLOOK

In this paper, a high- dv/dt test bench was used to perform insulation tests at extremely steep voltage slopes. With a comparison between 50 V/ns and 110 V/ns, it was shown that steep voltage slopes drastically decreases the lifetime of enameled wires. However, a PD-resistant additive in the enamel of the copper wires can increase the lifetime, for excitations with voltage slopes of up to 50 V/ns. At voltages slopes of 110 V/ns, this is not necessarily the case.

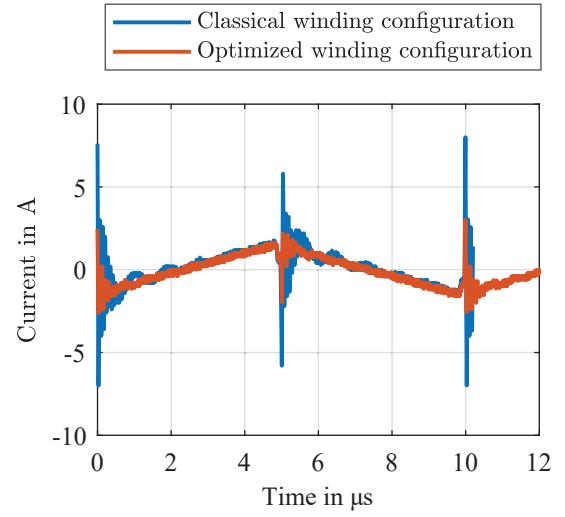


Figure 13. Current waveform of the single tooth with the classical winding configuration and the one with the optimized winding configuration when excited with 50 V/ns at a switching frequency of 100 kHz.

Furthermore, single-tooth coil windings of a twelve-phase machine have been investigated. For this purpose, the load dependency of the test bench was considered and the settings were adjusted according to the previously discussed definition of the voltage slope. The lifetime and PD behavior of single-tooth coil windings with and without a PD-resistant additive have been compared. The results are in accordance with the experiments performed with the twisted pairs of enameled wires.

Moreover, two different winding configurations of the single-tooth coil windings were reviewed. It was shown that an optimized winding configuration can increase the resonance frequency, decrease the coupling capacitance of the coil windings, and thus, decrease the displacement currents during the switching events.

Overall, it was shown that twisted-pair specimens can give early insight into the aging behavior of enameled wire. Furthermore, tendencies were shown that those insights are also translate applicable to insulation systems of coil windings. Additionally, for such systems, also the winding configuration has to be considered. The combination of a PD-resistant insulation system and an optimized winding configuration tends to increase the lifetime of coil windings, although for limited voltage slope steepness.

In future work, more specimens should be investigated to obtain statistical relevant results. Moreover, influencing factors on the aging behavior of insulation systems, such as the voltage slope, the peak voltage and the switching frequency, need to be investigated in more detail. Furthermore, the effect of the premature failure of PD-resistant enameled wires at voltage slopes of 110 V/ns should be further investigated, so that finally, countermeasures can be derived and the potential of WBG power semiconductor devices can be fully exploited.

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