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Partial discharge diagnostics on inverter-fed drives of electric vehicles

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Abstract In this paper, the possibilities of partial discharge measurement at square-wave voltages are discussed. The focus is on low-voltage machines, such as those used in electric vehicles. An insight into common measurement methods is given. In this work, high-frequency current transformers and near-field probes are used as sensors. The generation of a realistic steep-edged test voltage according to IEC/TS 61934 is also discussed and demonstrated on an inverter with silicon carbide semiconductors.
Experiments are conducted to compare the sensors used. A direct comparison between cable-based sensors (HFCT) and antennas (near-field probes) is provided. Resonance points to open motor windings according to IEC/TS 60034-27-5 and their significance for partial discharge measurement are also investigated. The results show that the high-frequency current transformers and the ball probe are able to detect PD even at steep voltage edges. Excitation with a fast voltage edge results in non-negligible overshoots in the overall system due to resonances. It can be shown that the partial discharges occur during these overvoltages.

Keywords High-frequency PD detection · HFCT · Near-field probes · SiC inverter

Teilentladungsdiagnostik an umrichtergespeisten Antrieben der Elektromobilität

Zusammenfassung In dieser Arbeit werden die Möglichkeiten der Teilentladungsmessung bei rechteckförmigen Spannungen erörtert. Der Fokus liegt auf Niederspannungsmaschinen, wie sie z. B. bei Elektrofahrzeugen eingesetzt werden. Es wird ein Einblick in gängige Messmethoden gegeben. Als Sensoren kommen in dieser Arbeit Hochfrequenzstromwandler und Nahfeldsonden zum Einsatz. Die Erzeugung einer realistischen steilflankigen Prüfspannung nach IEC/TS 61934 wird ebenfalls behandelt und an einem Wechselrichter mit Silizium-Karbid-Halbleitern demonstriert.
In Versuchen werden die eingesetzten Sensoren miteinander verglichen. Dabei wird ein direkter Vergleich zwischen kabelgebundenen Sensoren (HFCT) und Antennen (Nahfeldsonden) ermöglicht. Auch Resonanzstellen bei offenen Motorwicklungen nach IEC/TS 60034-27-5 und deren Bedeutung für die Teilentladungsmessung werden untersucht. Die Ergebnisse zeigen, dass die Hochfrequenzstromwandler und die Ballantenne auch bei steilen Spannungsflanken in der Lage sind, TE zu detektieren. Durch Anregung mit einer schnellen Spannungsflanke kommt es aufgrund von Resonanzen zu nicht vernachlässigbaren Überschwingern im Gesamtsystem. Es kann gezeigt werden, dass die Teilentladungen während dieser Überspannungen auftreten.

Schlüsselwörter Hochfrequenz-TE-Detektion · HFCT · Nahfeldsonde · SiC-Wechselrichter

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1 Introduction

Today's electric vehicles are operated with DC link voltages up to 800V. Steep voltage edges generated by the drive converters are another stress on the insulation systems. From a power electronics point of view, it makes sense to make the voltage edges as steep as possible to minimize switching losses. New semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) are used for this purpose. However, the steep edges and any overshoots associated with them place a heavy stress on the insulation systems [1].

A good way to examine and evaluate insulation systems is partial discharge (PD) diagnostics. In conventional standardized methods, such as IEC 60270, sinusoidal voltages are used primarily at mains frequency. In IEC 60270 partial discharges are detected in a frequency range below 1MHz. In general, an attempt is made to capture the partial discharges in the lowest possible frequency range to allow calculation of the apparent charge. Elaborate measures, such as filters, are used to eliminate or minimize any interference, irrespective of its origin. There are already some guidelines for this, e.g. IEC/TS 61934 and IEC/TS 60034-27-5. The importance of diagnostics of electric motors in the considered low voltage range and a monitoring method was presented e.g. in [2] for railroad motors. But PD diagnostics can also be useful for much smaller motors, such as those used in electric vehicles, e.g. to detect faults during the production process.

Nowadays, almost all drive units of medium and small power classes are supplied by converters. In electric vehicles, it is common to connect the inverter directly to the motor. The motor system thus receives the voltage stress directly through repetitive pulses. Due to the steep voltage edges, the conventional PD measurement results in very strong interference, which makes the evaluation of PD impossible. In order to be able to measure the PD at the original pulsed voltage, other methods must be used. For the investigation of drive units, wired methods or near field probes are suitable, which will be discussed in this paper. The problem with PD measurement via optical methods is that no light is transmitted through the motor housing.

To measure the PD in the laboratory, fully definable power electronic test sources must also be available. It is possible to use commercial high-voltage amplifiers for initial tests. However, you would then have to accept a reduction in power and switching speed. It also makes sense to consider the entire chain of effects from the inverter to the machine. For this reason, it makes sense to develop an own test sources based on SiC semiconductors. With these sources, single pulses as well as different modulation methods can be investigated.

2 PD measurement at voltage pulses

2.1 General

In principle, the methods from IEC/TS 61934 can be used to measure PD at steep voltage edges. It is important here that, unlike IEC 60270, PD is not measured in the low frequency range below 1MHz. Drive converters cause interference up to some hundreds of MHz, thus causing any measurement below these interference frequencies impossible. For this reason, IEC/TS 61934 suggests measurements in the higher frequency range of approximately 1GHz and the use of appropriate high-pass or band-pass filters.

2.2 Sensors

Three electrical sensor methods can be used to couple out the PD signals. These are decoupling via a coupling capacitor combined with a coupling quadripole, via an antenna or a high-frequency current transformer (HFCT). The measurement via external coupling capacitors is avoided in this work, since these do not occur in real applications for drive motors. The use of parasitic capacitances as coupling capacitance is difficult, since they are usually not precisely known and can change with rotor position. Antennas can be used to measure PD reliably. However, metallic housing parts can lead to shielding of the antenna. HFCT can be inserted directly into the feed lines. There is no shielding effect due to housing parts. However, the inductive motor windings lead to attenuation of the PD signal. Depending on the objective of the measurement and the device under test, both methods are suitable. In this work, both methods will be compared in order to evaluate a selection of suitable sensors for PD measurement. The focus in this work is on passive sensors for better comparability. An optimization with active components would be conceivable after the basic consideration. Table 1 shows the sensors used. The ball probe and stub probe are part of a commercially available near-field probe set for EMC test laboratories. There, they are normally used to detect sources of interference.

In order to suppress the interference range of the inverter, it is essential to use high-pass filters. In several own works [3–5] it has been shown that passive high-pass filters of 7th order directly at the sensor provide sufficient attenuation of the interference signal. Acoustic and optical methods can be used as alternative PD measurement methods, which serve as validation methods in this work.

Table 1 Selection of sensors used for PD decoupling

	HFCT	Ball Probe	Stub Probe
Freq.	up to 1 GHz	up to 3 GHz	up to 3 GHz
HP Filter	300 MHz	100 MHz	100 MHz

2.3 Signal analysis

A wide toolbox is available for the evaluation of the measured signals. Good results could be achieved, if the interfering signals of the source are already prefiltered with high-pass filters before the data acquisition. Some PD signal power in the lower frequency range is also suppressed using this method. Only in the higher frequency range does the signal components of the PD pulse outweigh the interference.

In [5] some evaluation possibilities in the time domain, frequency domain and in the combined time-frequency domain were presented. The simplest way to evaluate the prefiltered signals is directly in the time domain.

3 Test voltage sources

3.1 Overview

For the verification of possible influencing factors on the partial discharge at the test specimens from Sect. 4 different voltage sources are required. In order to be able to simulate steep-edged square wave voltages of modern inverters in the laboratory environment, a 3-level neutral point clamped inverter with IGBTs was built in [5] and a full-bridge inverter with SiC MOSFETs in [3]. Compared to commercially available inverters, the voltage shape can thus be adjusted much more flexibly, since there is access to all characteristic parameters. To ensure a sufficiently large voltage reserve for devices under test (DUTs) with a high PD inception voltage (RPDIV) and in case of voltage overshoots, semiconductors with a reverse voltage of 1.7 kV are selected.

Furthermore, test generators for EMC testing technology can be utilized to generate standardized, pulse-shaped voltages. Burst generators, for example, simulate transient noise interference with high slew rates. This allows to investigate the influence of high-frequency interference up into the MHz range.

For PD measurements, according to IEC/TS 61934, the following properties should be used to characterize the voltage pulses generated by the test voltage sources:

- Voltage waveform
- Repetition rate/ frequency
- Rise time
- Impulse duration
- Polarity

3.2 SiC full-bridge inverter

The self-developed full-bridge SiC inverter is used as a universal test voltage source in this paper. Figure 1 shows a photo of the 19″ rack-mount chassis of the inverter. The inverter is constructed using two identical SiC half-bridge modules. The two MOSFETs of a half-bridge module are driven via a plug-in gate driver board.

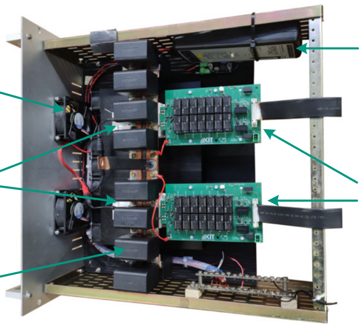

Fig. 1 Photo of the SiC inverter in a 19″ rack-mount chassis

Table 2 Characteristics of the SiC inverter

Parameter	Symbol	Adjustable value
DC link voltage	V_{dc}	max. 1400 V
Frequency	f_s	max. 100 kHz
Slew rate	dv/dt	1.23–15.92 kV/µs
Duty cycle	D	5–95 %
Phase shift	β	0–180°
Modulation	M	square wave, single pulse

The SiC inverter is fed from a DC link. A high-voltage generator is used as DC voltage source. Since the generator cannot be used as a sink, additional discharge resistors are integrated in the DC link setup. A capacitor bank of film capacitors in an additional chassis serves as energy storage for stabilizing the DC link voltage. Snubber film capacitors are located directly in the inverter chassis to provide the quick current pulses for the fast-switching SiC semiconductors. This avoids overshoots directly on the semiconductors and thus contributes to safety.

Table 2 shows all adjustable parameter values of the SiC inverter and shows the classification of the inverter according to IEC/TS 61934. As a special feature, the slew rate can be varied by the gate drivers. This is implemented using a resistive open-loop gate driver topology with a switchable external gate resistor array. In [3], the influence of the slew rate on the RPDIV was investigated on twisted-pair DUTs in this way. Via a graphical user interface, the parameters can be changed during operation on the laboratory PC.

4 Test samples

The choice of test specimens with the right abstraction model is an essential part of PD diagnostic for electrical machines. Special for electric vehicles the manufacturers often don't provide the whole motor, what makes the PD diagnostics more difficult. Therefore, this subsection should give a short overview about the possible and common used test samples, with references to additional literature. In general, the device under test must be kept as simple as possible. On the other hand, the device under test must be complex enough to represent all important effects. For electrical machines there are some potential problem areas in the insulation system. In classically wound machines, high potential differences between closely spaced enameled copper wires of different phases occur in the coil end. Here, a twisted pair is a simple test geometry. Twisted pairs are easy to manufacture according to DIN EN 60851-5. In [3], measurements have already been carried out on twisted pair test specimens. A pronounced self-healing effect on the PD inception voltage was observed. According to [6], this effect is less pronounced in impregnated devices under test or motors. This effect can be important in the development of test procedures. In addition, its effect on lifetime could be investigated. PD on twisted pairs was also investigated in [7] or [8], for example.

For hairpin motors, the hairpins can be used as test objects. However, care must be taken here to ensure that there is comparable contacting to that in the motor. Metal grit or salt water, for example, can be used as a contacting electrode.

The main insulation between the stator notch and the conductor can also be a problem area [9]. A replication of this problem area is made possible by a motorette, for example according to [10].

The complete geometries of the test specimens are of particular importance. In the simplest case, finished stators without rotors are suitable for this purpose. The examination of complete machines can also be interesting, for example, for quality control in the manufacturing process.

5 Experimental setup

In this paper, the measurement on stators and motors will be investigated in more detail. For this purpose, the setups according to Fig. 2 and 3 are used. Two identical 3 kW asynchronous motors are used as test specimens. The rotor was removed from one specimen so that the stator can be measured in detail. This test specimen will be referred to as the stator in the following. The other specimen was left in its original condition and will be called motor in the following.

To characterize the measurements, the test specimens are first shown in Fig. 2 according to IEC/TS 60034-27-5. At the same time, HFCT1, HFCT2, the ball probe (BP) and stub probe (SP) can be measured. The results can thus be validated by the standardized PD measuring instrument.

In Fig. 3 the inverter is used as the test source. HFCT1 and the two near-field probes are used as sensors. The voltage is measured as in Fig. 2 at the winding input and at the output respectively. The winding is in open circuit at the end, with non-negligible parasitic capacitances taking effect. Voltage measurements V1 and V2 were taken directly at the terminals of the motor. This is to minimize the effects of the line during the voltage measurement.

The position of the near-field probes is of great importance because the sensitivity decreases with increasing distance. Figure 4 shows how the sensors were placed in the stator. The holder for the ball probe is shown on the left and for the stub probe on the right. In the measurement application, both probes are used at the same time. For measurement on the motor, positioning the probes is more difficult because the housing cannot be opened. For this reason, the probes have been placed here next to the open terminal box.

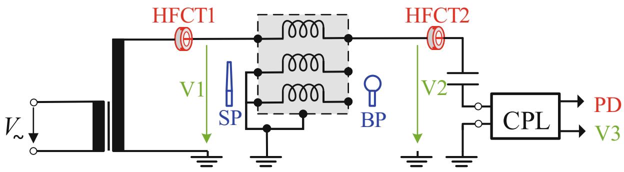

Fig. 2 Experimental setup for 50 Hz sine wave voltage

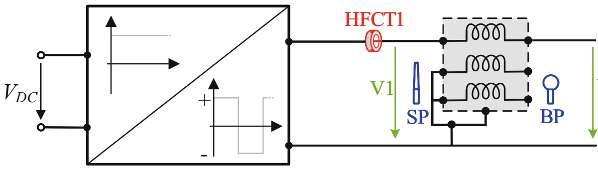

Fig. 3 Experimental setup for 1 kHz square wave voltage

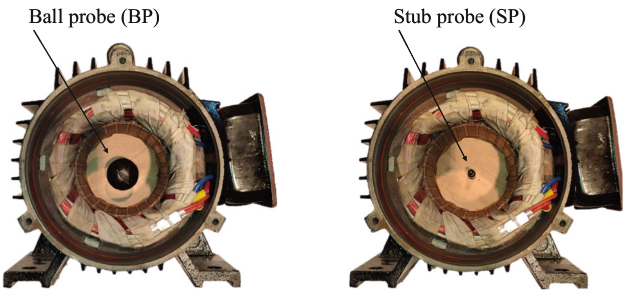

Fig. 4 Positions of the near-field probes in the stator. **a** ball probe, **b** stub probe

6 Results

6.1 Measurement at sine voltage

The measurements at sine voltage are used to validate the sensors. This is necessary because it is very important to be able to distinguish the PD signals from possible interferers. At 50 Hz, standardized PD measuring devices can be used for comparison, which was also done in this work. The procedure is described in [4]. The results show that the sensors can detect PD in accordance with the standard PD measurement device.

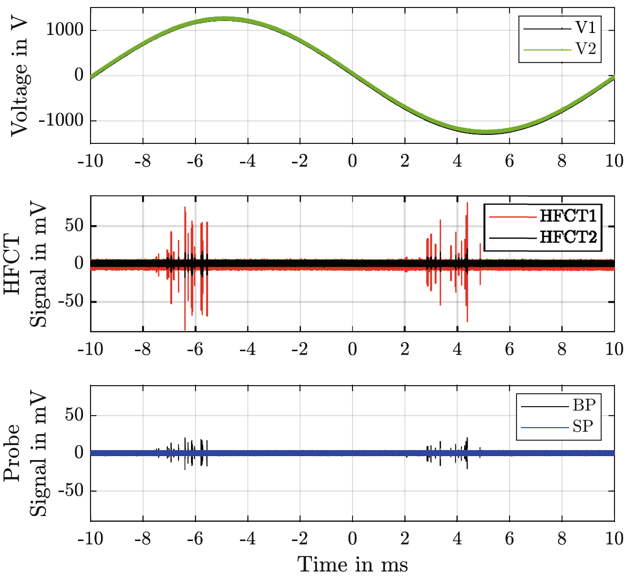

Fig. 5 Masurement at 50 Hz sine voltage

Figure 5 shows the results for a sinusoidal voltage with a frequency of 50 Hz and an amplitude of 1295 V. This voltage is slightly above the PD inception voltage as a steady state for the occurrence of PD is to be achieved. Any self-healing processes [3] should therefore not be considered. The measurement was performed in envelope mode to determine a distribution of PD pulses. It can be clearly seen that PD can be detected with HFCT1, HFCT2 as well as with the ball probe. In contrast, the stub probe is significantly less sensitive and does not show any peak signal. It can also be seen that the HFCT provides a higher signal amplitude than the ball probe. However, as shown in [4], the amplitude level of the HFCT sensors is strongly dependent on the damping of the winding and consequently on the positioning of the sensors and the locality of the PD.

6.2 *Effect of the square-wave voltage on the test specimen*

Since electrical machines are subjected to steep-edged voltages during inverter operation, their effect must be investigated. For this purpose, there are already some works such as [1] or [11]. Nevertheless, since here according to IEC/TS 60034-27-5 the winding is open it is important for this work to analyze the used stator in more detail. For this reason, an impedance analyzer is first connected instead of the inverter from Fig. 3 to determine possible resonance points. The line resistance, the inductance of the winding and the supply line and the leakage capacitances are effective here and form an LCR series resonant circuit in the first approximation.

Figure 6 shows on the left axis in double logarithmic scaling the magnitude of the absolute impedance. On the right axis the phase response is plotted. At a

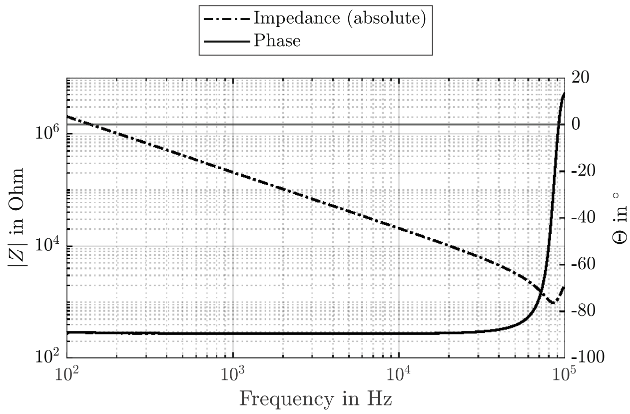

Fig. 6 Frequency response of absolute impedance and phase measured at the stator

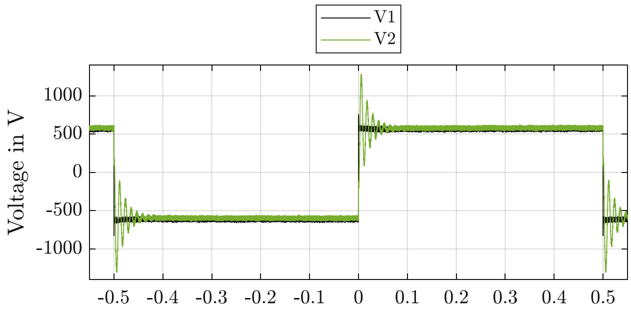

Fig. 7 Measured voltage waveform at the stator

frequency of 91.7 kHz a resonance point is clearly visible.

Figure 7 shows the measured voltage waveform with the inverter connected according to Fig. 3 and a DC link voltage of 575 V. V1 in black shows the measurement at the input of the device under test and V2 in green at the open winding. As an overview, a whole period is plotted in Fig. 8, the ringing is resolved higher. The measured frequency of the overshoot is 84 kHz. The deviation from the behavior shown in Fig. 6 can be explained by the fact that the cables to the inverter are added to the setup, which slightly shift the resonance point due to their inductance.

6.3 *PD measurement at square wave voltage*

Now the stator and the motor are examined for PD according to Fig. 3. The self-developed SiC converter is used for this purpose. The fundamental frequency of the square wave voltage is set to 1 kHz. The slew rate is set to 6.5 kV/µs. Figure 8 shows the results on the falling edge of the stator. The falling edge is only used as an example. With regard to the PD behavior, there are no discernible differences between the falling and rising edge. The PD events were superimposed in envelope mode. In the upper graph, the resonance can be seen in green. In the middle, the PD events measured with HFCT1 are plotted. In the lower plot the

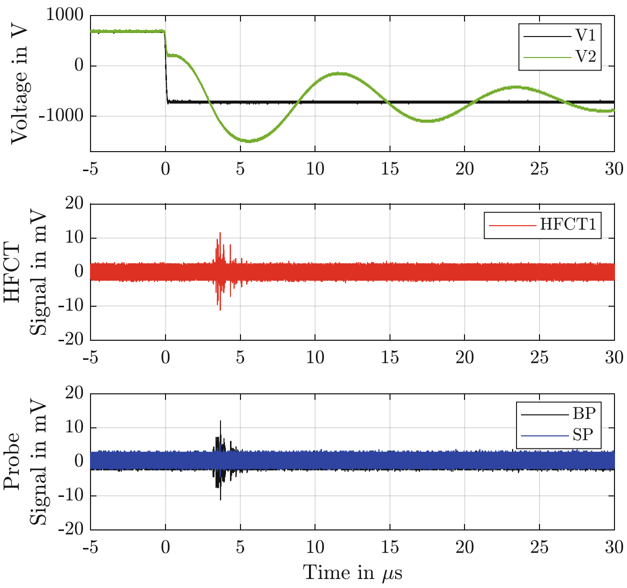

Fig. 8 PD measurement at stator with falling edge in envelope mode

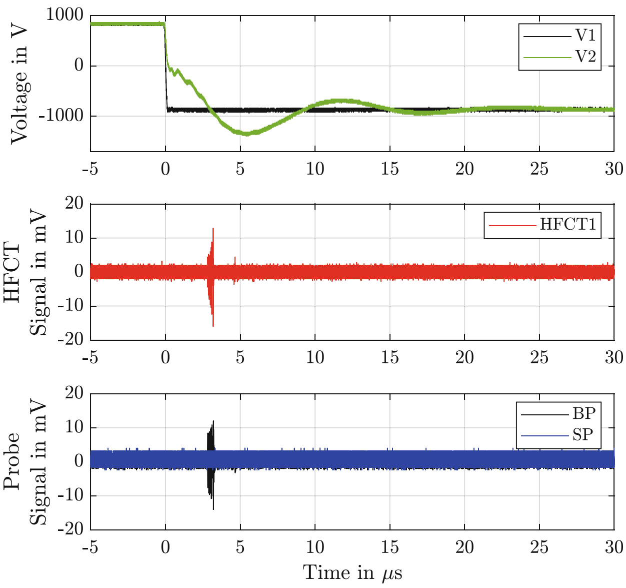

Fig. 9 PD measurement at motor with falling edge in envelope mode

results of the near field probes are shown. All measurements were recorded synchronously at the same time. PD can thus be detected with HFCT as well as with the ball probe.

Figure 9 shows the same measurement on the motor. Since the probes cannot be inserted into the stator here, they were placed above the open terminal box. It is noticeable that the ball probe can detect PD despite the closed housing. A verification with a UV PD localizer ruled out the possibility of external PD. It would be possible that the PD is emitted via the connection cables, or that it is propagated through the opening of the terminal box to the motor. With regard to the phase position, the measurements are comparable to the measurement with sinusoidal voltage. This is an interesting result, since the frequencies of the voltages are so far different from each other. The resonance frequency at the motor is slightly smaller than at the stator. The damping, on the other hand, is much greater. As a result, the overshoot decays more quickly and its amplitude is also not as pronounced.

7 Conclusion

In this work, the measurement of partial discharges in inverter-fed machines is investigated. The focus is on low-voltage machines, such as those used today in electric vehicles. An investigation for PD makes sense because, on the one hand, materials are increasingly being stressed towards their limits and, on the other hand, an occurrence of PD can quickly lead to failure of the insulation system.

An overview of possible methods and sensors for PD measurement in this application area is given. For PD measurement at steep edged voltages a measurement in the high MHz range is necessary. Current transformers or antennas are mainly used as sensors. In this work the focus is on HFCT and commercial near-field probes used in EMC laboratories.

Especially important for the measurement of PD is the test voltage source. In this paper, a specially developed SiC inverter is presented, where it is possible to set all parameters including the slew rate. In addition, other common test sources are addressed.

The measurements in this paper focus on passive sensors to ensure comparability. Both HFCT and near-field probes in the form of a ball probe and a stub probe are used as sensors. The signals are pre-filtered by 7th order passive high pass filters to suppress the interference from the test source.

The results show that for inductive DUTs, the possible resonance points due to the inductance and stray capacitances must be taken into account. These resonances are excited by the steep-edged voltage pulse and can generate overvoltages in the overall system. The measurement of PD is possible with the ball probe as well as with the HFCT. However, due to the effective inductances, these pulses can be strongly attenuated. For a PD measurement, attention must therefore also be paid to the positioning of the sensors.

The information on the structure of the test setup and the comparison of the different sensor methods can be used in the future to improve test benches and e.g. to facilitate the selection of sensors for different PD diagnostic applications

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