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Influence of conductive particle contamination on the insulation system of rotating electrical machines with direct oil cooling

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Abstract: An integration of the electrical machine and the gearbox is attracting particular attention for the design of modern electric and hybrid drive trains, since it saves overall space and subsequently increases the power density. Another benefit of a high level of integration is that it enables a combined application of oils as both cooling fluid for the electrical machine and as lubrication fluid for the transmission system. In this way, the power density of the integrated drive train can be further increased. During the oil cycling, conductive contaminations may be introduced and subsequently have an influence on the function of the insulation system of the electrical machine. In the present work, the influences of the cooling oil and its conductive contaminations, conductive particles as well as their combination with humidity, on the electrical and dielectric properties of the insulation system are studied. The results show that by application of the cooling oil, the partial discharge inception voltage (PDIV) of the winding insulation increases significantly so that an electrical breakdown is prone to happen before a partial discharge (PD) occurs. With increasing particle contamination, the PDIV of the insulation system decreases significantly, while the capacitance increases. Besides, conductive particles and humidity decrease the surface resistance and surface breakdown voltage of the insulation papers significantly. The results indicate that the conductive particle contaminations can play an important role for the electrical degradation of the insulation system.

Key words: cooling, insulation system, particle contamination, partial discharge, surface resistance



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1. Introduction

This article is dedicated to Professor Andrzej Demenko and Professor Lech Nowak in recognition of their lifetime contribution to the field of Electric Machines.

In the recent decade, the concept of direct-oil-cooling has attracted particular attention, especially in the area of high-power traction machines [1–5]. Direct-oil-cooling may include stator and rotor cooling with flashed coolant as well as end-winding cooling with coolant spray. A common feature of the aforementioned cooling methods is that the coolant is in direct contact with the inner machine components, especially with the insulation system. The insulation system is a crucial component of the electrical machine, since it determines the thermal capability and the lifetime of the entire machine. Therefore, the choice of the coolant should not only consider the thermal performance, but also the dielectric properties of the coolant as well as its influence on the insulation system. From this point of view, the cooling fluid should be regarded as part of the insulation system of the cooled machine, which means that the coolant should also have appropriate dielectric properties. In comparison to the traditional water-based cooling fluids, the lubricating oils are more competitive in this aspect. In practice, the automotive transmission fluid (ATF) has been used for this purpose [6]. The combined use of oils as both lubricant for the transmission system and coolant for the electrical machine is a significant progress for the design of modern electric drive system. Typical applications of this concept are in the area of the electric and hybrid vehicles [5, 7], in which the electrical machines are integrated into the transmission system. The current state of the art is that the machine designers are mainly focusing on the improvement of the cooling system to increase the cooling efficiency, while the lubricant producers are more interested in improving the oil properties, such as a reduction of the viscosity for a better mobility. However, basic issues such as the particle contaminations of the oils during the cycling process, the material compatibility between oils and the machine components, have not been fully understood and investigated.

In the area of transformers there have been various studies regarding the issue of particle contaminations in the oils. [8, 9] studied the influence of copper particle contaminations on the electrical performance of the insulation oils in the transformer, [10–12] indicate that the contaminated particles in the insulation oils of the transformer are mainly metallic particles in the scale of micrometer including copper, iron and aluminum particles. Besides, nonmetallic particles such as carbon, cellulose fiber and dust can also exist. [12, 13] observe the accumulation of different particle contaminations in the transformer oil and the formation of “bridges” between the two electrodes, which may have a destructive effect on the transformer oil. In the rotating electrical machine, the researchers have already noticed the problem of the particle contaminations, though there is not yet intensive study on the mechanisms. [7] observes an increasing number of aluminum and iron particles during operation of an integrated drive system, and the particle sizes are usually in the micrometer range.

With the development of the modern electric traction machine, the required dc-link voltage is increasing. Besides, due to the development of the power electronics, the voltage slew rate du/dt increases, which leads to a significant increase of the voltage overshoot at the machine terminals [14]. In addition, the electrical field is usually not evenly distributed and in some places field concentration may occur, particularly at the end winding [15] or where foreign contaminations exist [16]. All these factors increase the risk of surface discharge and surface

breakdown of the insulation materials. If the tangential components of the electric field strength on the surface of the insulation material exceeds the discharge field strength, surface discharges occur along the insulation surface [17]. For instance, [16] points out that the contaminated metallic oxides on the stator winding may lead to intense surface discharge and tracking. Therefore, the issue of creepage along the surface of the insulation materials in a low voltage electrical machine should also be considered properly. Figure 1 distinguishes the air distance and the creepage distance along the surface of the insulation material. In the standard IEC 60664-2-1 [18] it is pointed out that the minimum creepage distance should be determined considering the environmental influences such as particle contaminations and humidity. The contaminations in the micro-scale can be classified into four degrees, as summarized in Table 1, according to the standard IEC 60664-1 [19]. However, the aforementioned environmental influence is basically based on the practical experience, and therefore, it should be studied intensively. In summary, the study of the effect of particle contaminations, especially for the conductive particles, on the electrical performance of the insulation system of the electrical machine is still in its infancy. Much effort is still necessary for a better understanding on this issue, and guidelines are to be improved for the design of the rotating electrical machine and the electric drive system.

In the present work, the influence of conductive particles on the insulation system of a rotating electrical machine is studied. Particularly, the influences of copper particles on the initiation of

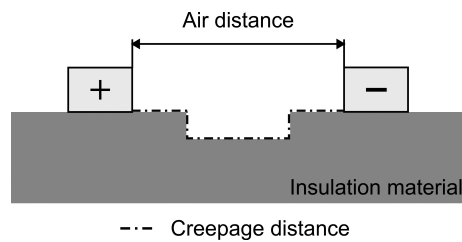


Fig. 1. Demonstration of the air distance and creepage distance

Table 1. Contamination grades and their effect on the insulation system of the low voltage electrical machine according to the standard IEC 60664-1 [19]

Contamination grade	Description	Impact on the insulation
I	No or only dry, non-conductive pollution occurs	Ignorable
II	Only non-conductive pollution occurs. Occasionally can be temporarily conductive due to condensation	Slight, should be considered
III	Conductive pollution occurs or dry, non-conductive pollution that becomes conductive as condensation is expected	Moderate, must be considered
IV	Permanent conductive pollution occurs, caused by conductive dust, rain or moisture	Extreme, significant effect on the minimum creepage distance

partial discharge (PD) and electrical breakdown, the changes of the capacitance and the dielectric loss factor of the winding insulation are studied experimentally. Besides, the influence of copper particles as well as the combined effect of copper particles and humidity on the surface properties of the insulation paper, including the surface resistance and surface breakdown voltage, will be studied in details. The goal of the present work is to provide some guidance on the design of the cooling system and typically on the combined use of oils in electric drive systems. The highlights of the present work are that it provides an overview about the contamination phenomena in the cooling and lubricating oils in practice and the potential influences of conductive contaminations of the oils on the insulation system of the electrical machine. Besides, basic testing methods are also developed for the relevant studies.

2. Methodology

To understand the influence of conductive contaminations of oils on the insulation system of the electrical machine, an experimental strategy is worked out, as demonstrated in Fig. 2. On one hand, field oils in the electric motor and in the transmission system are analyzed to verify the phenomenon of particle contaminations of cooling oils during the service in the electric drive train system. On the other hand, based on the particle size and concentration distributions of the field oils, laboratory oils with defined particle contaminations are mixed for the experimental study. The experiment is mainly concentrated on the following influences of the conductive particles:

- The occurrence of PDs of the winding insulation.
- The surface properties of the insulation paper, including the surface resistance and the surface breakdown voltage.

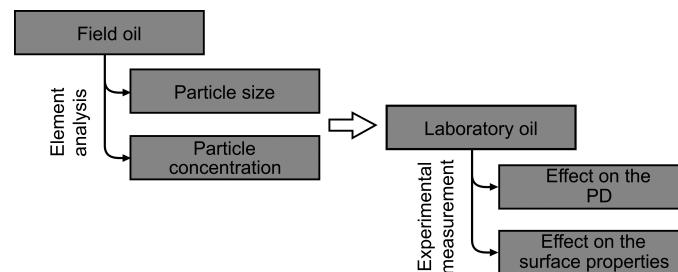


Fig. 2. Overview of the experimental strategy of the present work

2.1. Particle contaminations of oils in the electric drive systems

As mentioned above, one of the challenges for a combined use of oils in the entire drive system is particle contamination. Especially in the transmission system, large metallic wear particles are produced gradually during operation. While in the electrical machine, particles may originate from residuals of the manufacturing process, dust, wear particles at the shaft, material losses of the impregnation due to rotation and vibration as well as material degradation at high operation temperatures. In order to determine the sources of the particle contaminations in the oil, field oils

are analyzed in the present work. For this purpose, one type of commercial e-motive oil is applied to the electrical machine for the cooling purpose and to the transmission system as lubricant in an electric motorbike, separately. The size distribution of the particle contaminations of the served oils in both the electric motor and the transmission system is analyzed at the initial state and after a mileage of 10 000 km with the dynamic light scattering (DLS) technology. As shown in Fig. 3, the average particle size of the new oil is around 1 nm, which is mainly contributed by the polymer-additives. After a mileage of 10 000 km the size distribution of the particles in the electric motor shifts to the range of 10 nm–100 nm. In comparison, the particle size in the transmission system shifts to the range of 100 nm–1 000 nm, which are probably large wear particles of the gears. Besides, very large particles within the micrometer range are also observed with a very small number. Element analysis is also conducted with these oils. The results show that the conductive particle contaminations in both fields are mainly composed of iron, which is up to 186 mg/kg (corresponding to 0.16 g/L with an oil density of 850 g/L), as shown in Table 2.

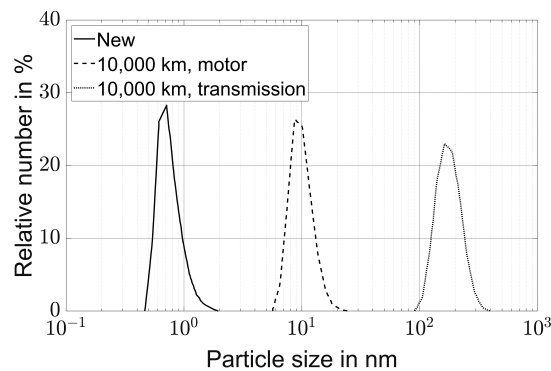


Fig. 3. Particle size distribution in the new oil, in the electrical motor field oil as well as in the transmission system field oil after a mileage of 10 000 km

Table 2. Element analysis of the field oils in the electrical motor and the transmission system

Element	Concentration in mg/kg		
	New oil (as received)	Motor oil (after 10 000 km)	Transmission oil (after 10 000 km)
Fe	1	54	186
Cu	< 1	1	< 1
Pb	< 1	< 1	< 1
Sn	< 1	< 1	< 1
Cr	< 1	< 1	3
Al	< 1	< 1	3
Ni	< 1	< 1	2

Besides, other elements such as copper (in the electrical motor oil), chromium, aluminum and nickel (in the transmission oil) also exist with a lower concentration.

From this point of view, the electrical machine may have a risk of degradation from these particle contaminations both electrically and mechanically. On one hand, the machine could suffer from the friction of the particles during rotation and vibration, on the other hand, the conductive particles existing in the insulation system will have an effect on the distribution of the electrical field. As a consequence, local electrical failure may occur, which may make the entire machine unusable. Therefore, it is important to study the effect of the conductive particles on the dielectric properties of the insulation system. In the following work, the influences of copper particles in a size scale of micrometer on the partial discharge inception voltage (PDIV), capacitance and the dielectric loss factor of the insulation system are studied.

2.2. Preparation of the laboratory oils

Through the analysis of the field oils both in the electric motor and in the transmission system, it is ensured that the particle contaminations, particularly the contamination of conductive particles, can be generated during the service of the oils. Firstly, due to the fact of limited availability and uncontrollability of the field oil, laboratory oils with certain particle contaminations are produced for the further experimental study. Besides, considering the quite limited mileage of the relevant field oils, the particle concentrations in the laboratory oil are extended from 0.16 g/L to 1.5 g/L, assuming that the particle concentration increases with increasing mileages. In addition, despite that the iron particles are dominant contaminations in both electric motor and the transmission system, the copper particles are chosen for the experimental study as the worst case, considering the fact that copper has a much higher electrical conductivity than iron. Copper particles are added to one commercial ATF to simulate the conductive contaminations of the cooling fluid.

2.3. Sample preparation and measurement of the winding insulation

For the study of the influence of particle contaminations on the occurrence of PDs on the insulation windings, the enameled wire Damid 200, Grade 2 is used, the specifications of the materials are listed in Table 3. Twisted pairs are produced according to the standard [20]. Copper particles with an average particle size of 5 μm are used for this experiment. Each homogeneously mixed solution with a copper content of 0 g/L, 0.4 g/L, 0.8 g/L and 1.2 g/L is impregnated on the surface of 20 twisted pairs, respectively. The impregnated twisted pairs are subsequently subjected to the electrical tests. Figure 4(a) shows oil-impregnated twisted pair, the zoomed part of the twisted pairs gives evidence of copper particles on the surface of the sample.

To characterize the influence of the oil and the copper particles on the dielectric properties of the twisted pairs, the capacitance C_p and dielectric loss factor $\tan(\delta)$ are measured at 1 kHz and 10 kHz, respectively. The PDIV is measured under a sinusoidal voltage at 50 kHz. Besides, the repetitive partial discharge inception voltage (RPDIV) is also measured at a surge voltage to simulate the effect of fast switching IGBTs at high frequencies on the electrical winding system of an inverter-fed electrical machine. A schematic of the test bench for the PDIV and RPDIV measurements is demonstrated in Fig. 4(b). During the PDIV test with a sinusoidal voltage, the capacitive current between the conductors of the twisted pair is monitored. An overshoot

Table 3. Specifications of the materials used for the experiments

Material	Enameled wire: Damid 200, Grade 2	Insulation paper: AHA
Composition	Dual-coating: polyester-imide + polyamide-imide	Three layers: aramid + polyimide + aramid
Thermal class	200°C	180°C
Application	Mainly as stator winding of electrical motors and generators	Mainly as slot and phase insulation or wedge of electrical motors
Diameter,thickness	Wire diameter of 1 mm, the thickness of the insulation coating is corresponding to the requirement of the standard IEC 60317-0-1:2013 [21]	Thickness of 0.3 mm
Specific resistance	–	Surface $\sigma_s = 10^{15}\Omega$ Volume $\rho_v = 10^{15}\Omega \text{ mm}$

current is detected on the occurrence of PD. During the RPDIV test with a surge voltage, a high-frequency antenna is used to detect the signals of PD. With the help of an external oscilloscope, the corresponding current can be captured when signals of the PD or even an arc occur. With this approach, the intensity of the PD and the arc can be evaluated. The PD is usually regarded as the first sign of winding failure, usually the machine fails quickly within several hours under the effect of PDs. However, the machine may fail immediately after an arc occurs.

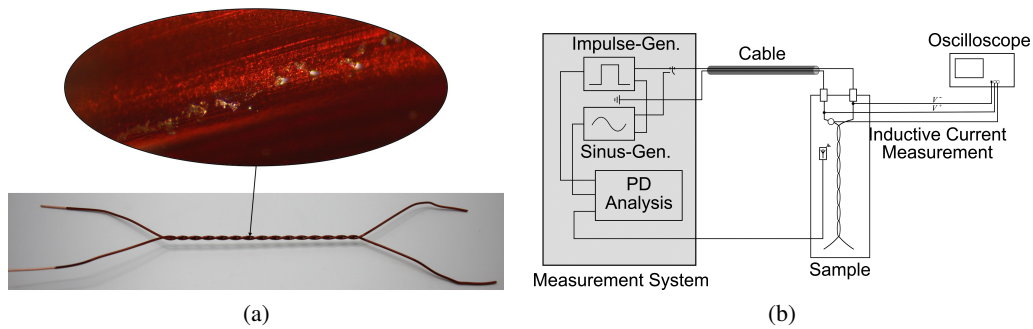


Fig. 4. (a) Oil impregnated twisted pair and (b) the setup of the PD-measurement test bench

The basic difference between an arc and a PD lie on the fact that the arc leads directly to a conductive connection between two copper electrodes, whereas PD does not bridge the entire insulation. An arc can occur in both liquid and gas, correspondingly with a much higher capacitive current, while a PD occurs only in gases with limited capacitive current. Therefore, in the present work, by monitoring the amplitude of the capacitive current, a PD or an arc is distinguished.

2.4. Sample preparation and measurement of the insulation paper

To study the effect of conductive contaminations on the surface properties of the insulation paper, the AHA insulation paper is used, the specifications are also listed in Table 3. A certain amount of laboratory oils with a copper content of 0 g/L, 0.1 g/L, 0.5 g/L as well as 1.5 g/L is impregnated on the gaps of three insulation paper samples, respectively. The copper particles with an average size of 38 μm are used in this experiment. Three samples are prepared for each measuring point. Figure 5(a) shows the setup of the resistance measurement system and the geometry of the sample. The setup of the electrodes is referring to the standard IEC 62631-3-2 [22]. To improve the contact between the paper sample and the electrode, both sides of the papers are painted with a graphite layer. To avoid discharges in the air typically during the measurement of the surface breakdown voltage, the distance between the positive and negative electrodes are set much larger than the effective surface gap d , namely the distance between the graphite electrode.

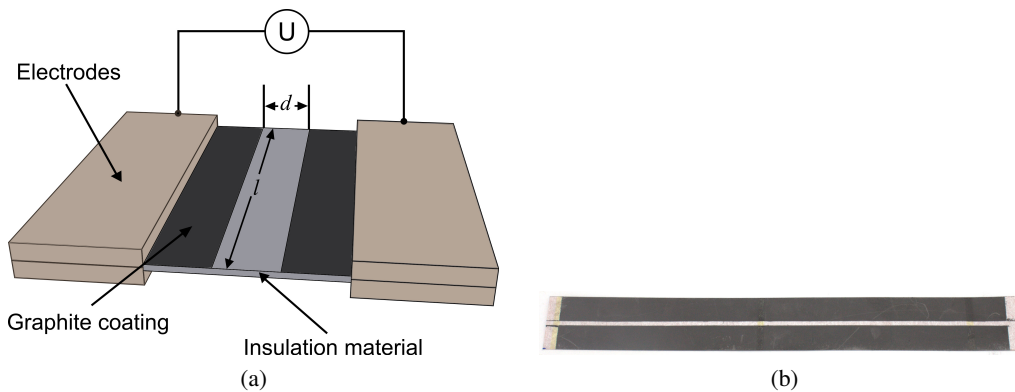


Fig. 5. Setup for the surface resistance measurement of the insulation papers: (a) test electrodes and (b) oil-impregnated paper sample

As shown in Fig. 6, the specific surface resistance σ_s is determined by the measurement of the current flowing through the surface I_s :

$$\sigma_s = 2 \cdot \frac{U}{I_s} \cdot \frac{l}{d}, \quad (1)$$

where: U is the supplied DC-voltage, l and d are the effective length and the effective distance of the insulation paper gap between two electrodes, as indicated in Fig. 5(a). For the AHA insulation paper used in the present study, the specific surface resistance σ_s and specific volume resistance ρ_v are given in Table 3. The relation between the specific resistance and the resistance under the given geometry can be expressed by:

$$\sigma_s = R_s \cdot \frac{l}{d}, \quad (2)$$

$$\rho_v = R_v \cdot \frac{t \cdot l}{d}, \quad (3)$$

where t is the thickness of the insulation paper. Applying the actual geometry of the samples ($d = 2 \text{ mm}$, $l = 200 \text{ mm}$), it can be calculated that the surface resistance $R_s = 10 \cdot 10^{12} \Omega$ and the volume resistance $R_v = 40 \cdot 10^{15} \Omega$, which means that $R_v \gg R_s$, therefore, the total resistance measured with the current setup R_{total} can be expressed as:

$$R_{\text{total}} = \frac{\frac{R_s}{2} \cdot R_v}{\frac{R_s}{2} + R_v} \approx \frac{R_s}{2} \quad (4)$$

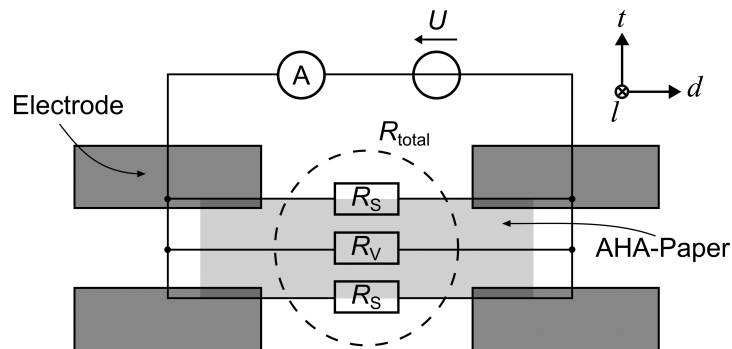


Fig. 6. Equivalent circuit diagram of the resistance measurement

The surface breakdown voltage is measured with the same electrode and the samples as well as the PD-measurement system as shown in Fig. 4(b). During the test, a sinusoidal voltage (50 kHz) is applied on the electrode, the amplitude of the voltage increases gradually until the detected inductive current is over 0.1 mA, the measured voltage is corresponding to the surface breakdown voltage.

Besides, to study the combinational effect of conductive particles with the humidity, the same samples, which are used for the surface resistance and surface breakdown voltage measurement, are stored in the climate chamber with a relative humidity of 95% at 25°C for 10 minutes before they are subjected to the surface breakdown voltage tests.

3. Results and discussion

3.1. Influence of the oil on the PD

As mentioned above, the cooling oil in the electrical machine should possess appropriate dielectric properties, since it is in direct contact with the windings. As the presence of the oil removes the voids between the insulated conductors, the application of oils in the electrical machine is expected to strengthen the electrical insulation and reduce the risk of PD. In other words, the oil can be regarded as one part of the insulation system. As shown in Fig. 7, both the PDIV and the RPDIV increase by about three times by impregnating the ATF on the surface of the twisted pair.

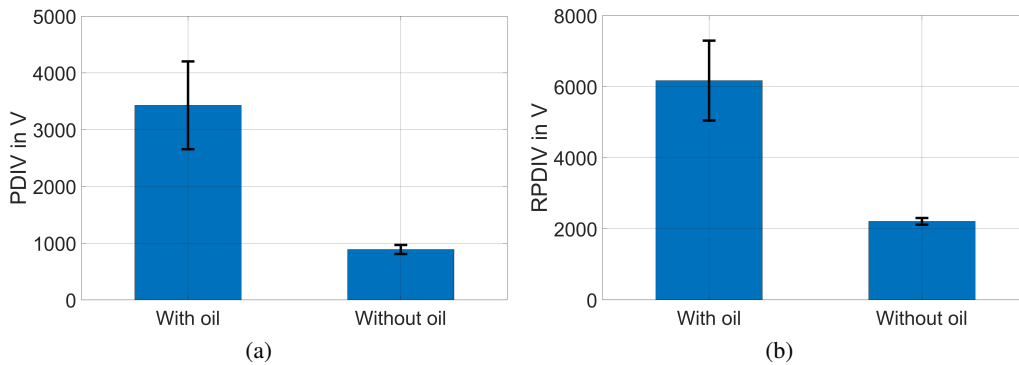


Fig. 7. Influence of the oil impregnation on (a) the PDIV of the twisted pair under a sinusoidal voltage and on (b) the RPDIV of the twisted pair under a surge voltage

During the RPDIV test under a surge voltage, the measured currents at the terminals of the oil-impregnated samples at the RPDIV are generally much larger than those of the dry samples, as shown in Fig. 8. Such a high amplitude of the current indicates a signal of arc or electrical breakdown by the RPDIVs of the oil-impregnated samples, more than just partial discharge. Therefore, it can be concluded that the oil-impregnated windings are prone to breakdown directly before a partial discharge is detected under a surge voltage. From this point of view, some criteria should also be adjusted properly during the machine design. The operation voltage must be lower than the RPDIV or the breakdown voltage, depending on the specific working environment:

- for the specimen without oil, the voltage threshold equals the RPDIV,
- for the specimen with oil, the voltage threshold equals the breakdown voltage.

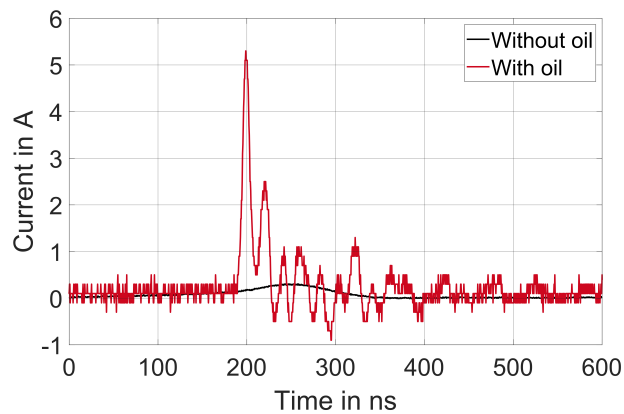


Fig. 8. The measured current signals at the specimen terminals when the RPDIV is detected by the PD-measurement system under a surge voltage

3.2. Influence of copper particles on the PD

In general, the low-voltage electrical machine must be designed being PD free, since the insulation system will fail in a short time under the condition of PD [14]. Therefore, the PD test can provide a criterion to estimate the life of the material: when the PDIV (or RPDIV) is below a crucial value, the material is determined as failed [23]. Generally, the material degradation obeys the Weibull distribution. The cumulative distribution function of a two-parameter Weibull distribution can be expressed as:

$$P(U) = 1 - \exp\left(-\left(\frac{U}{\alpha}\right)^\beta\right), \quad U > 0, \quad \alpha > 0, \quad \beta > 0, \quad (5)$$

where: $P(U)$ denotes the probability of the occurrence of PD at the voltage level of U , α and β are the scale parameter and the shape parameter, respectively.

Figure 9 shows the accumulative Weibull distribution of the measured PDIV and RPDIV under the sinusoidal and surge voltage with different contents of copper particles, respectively. As shown in both figures, the measured PDIVs are in good coincidence with the Weibull distribution. The fitted parameters of the Weibull distribution are summarized in Table 4 according to (5). Specifically, the values of the parameter α in Table 4 indicate the level of PDIV and RPDIV at a probability of 63.2%.

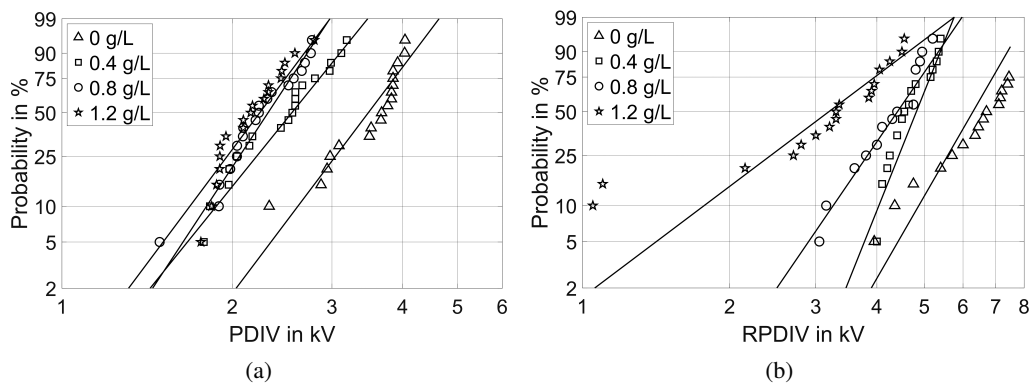


Fig. 9. Influence of the copper particles on the Weibull distribution of (a) the PDIV of the twisted pair under a sinusoidal voltage and (b) the RPDIV of the twisted pair under a surge voltage

The results show that the PDIV and the RPDIV decrease significantly with increasing content of the copper particles. This phenomenon can be explained with the high conductivity of the copper particles in comparison to the insulation materials between the two adjacent winding turns. As illustrated in Fig. 10, the twisted pair can be simplified as a two-plate capacitor since it is much larger than the copper particles. The distribution of the electrical field between the two windings can be distorted and the electrical field strength increases locally due to the charged copper particles. Besides, the copper particles accumulate between the electrodes and form a conductive “bridge”, which is as reported in [12, 13], mainly responsible for the occurrence of

Table 4. Parameters of the Weibull distribution for the tests with sinusoidal and surge voltage forms

Cu content in g/L	Sinusoidal		Surge	
	α in V	β	α in V	β
0	3677.18	6.57	6607.61	7.39
0.4	2704.95	6.13	4986.39	10.66
0.8	2428.50	7.53	4673.57	6.23
1.2	2363.54	6.62	3577.52	3.21

the PD and electrical breakdown. Moreover, with increasing copper content the “bridge” is more prone to form. As a result, the PDIV is reduced with increasing copper content.

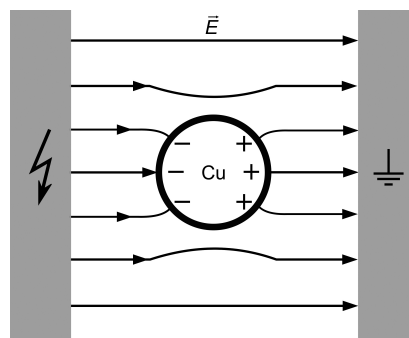


Fig. 10. Influence of copper particles on the distribution of the electrical field

3.3. Influence of copper particles on the capacitance and dielectric loss factor

The capacitance measurement indicates the losses or gains of the impregnations, as well as contaminations. Figure 11(a) shows that the capacitance of the oil-impregnated twisted pairs increases slightly with increasing copper particles at 1 kHz and 10 kHz. Assuming that the two adjacent windings can be regarded as a two-plate capacitor, the capacitance C_p between the two conductors can be expressed with the following equation:

$$C_p = \epsilon_0 \cdot \epsilon_r \cdot \frac{A}{D}, \tag{6}$$

where: ϵ_0 denotes the permittivity of free space, ϵ_r indicates the relative permittivity of the dielectric material between the capacitor, A is the area of the plate and D the distance between the plates. When the windings are impregnated with an insulation material such as epoxy and oil, the capacitance of the system increases since the permittivity of the impregnation materials are larger than that of the air. As demonstrated in Fig. 10, the copper particles are charged under the electrical field. Therefore, besides the random thermal motion, the charged copper particle also behaves as a polar molecule and have a motion tendency along the electrical field.

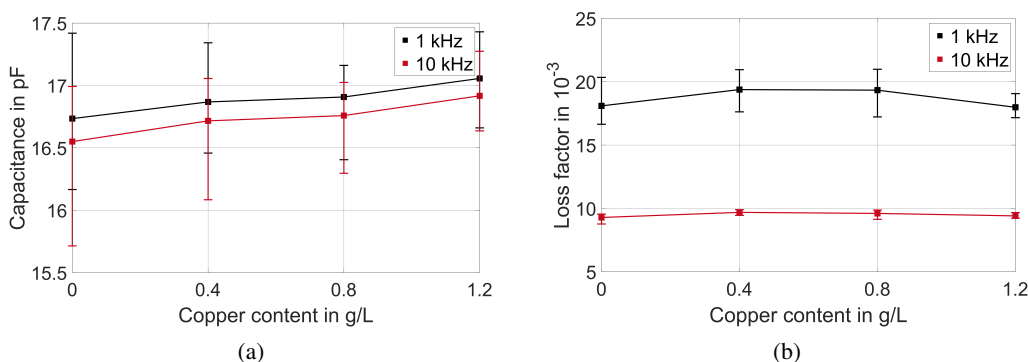


Fig. 11. Influence of the concentration of the copper particles on (a) the capacitance of the twisted pair and on (b) the dielectric loss factor of the twisted pair

According to [12,24], there are generally three types of polarization in the contaminated oil, space charge polarization at the interface of the oil and the copper particles, inner polarization of the oil and copper molecules, as well as dipole orientation polarization of both types of molecules. The inner polarization and the dipole orientation polarization take a very short time and can be sufficiently accomplished even at high frequencies. The space charge polarization depends on the existing interfaces. The more copper particles in the oil, the more area of the interface for the space charge, accordingly, the higher the relative permittivity of the contaminated oil, thus, the higher the resulting capacitance. But this is mainly valid at low frequencies, since the space charge polarization requires a relative longer time, its effect on the relative permittivity of the contaminated oil reduces with an increasing frequency. That could explain the slight increasing tendency of the capacitance with increasing copper particle contamination at 1 kHz and 10 kHz, as shown in Fig. 11(a).

A high-quality insulation material should have a low dielectric loss factor $\tan(\delta)$. In this present work, the dielectric loss factors of samples with different copper contents are also measured. As shown in Fig. 11(b) the dependence of $\tan(\delta)$ on the copper content is not as significant as the capacitance. Especially at a higher frequency (10 kHz), the value stays almost constant, which indicates that the characterization of the dielectric losses may not be sufficiently sensitive for the evaluation of particle contaminations in this work.

3.4. Influence of copper particles on the surface properties of the insulation papers

Figure 12 and Fig. 13 show the influence of increasing copper concentration on the surface resistance and the surface breakdown voltage of the insulation paper, respectively. As shown in the results, the dielectric properties along the surface of the material decreases significantly even at a very low copper concentration. Specifically, the surface resistance decreases by 85.25% and the surface breakdown voltage decreases by 10.47% at a copper concentration of 0.1 g/L, respectively. With increasing copper concentration, the surface properties of the material decrease gradually, which is however, not as sensitive as in the low concentration region. It indicates that even a very low concentration of conductive particles could also result in significant degradation

of the dielectric properties of the insulation materials. As a result, the entire insulation system as well as the entire machine could fail due to local electrical failure.

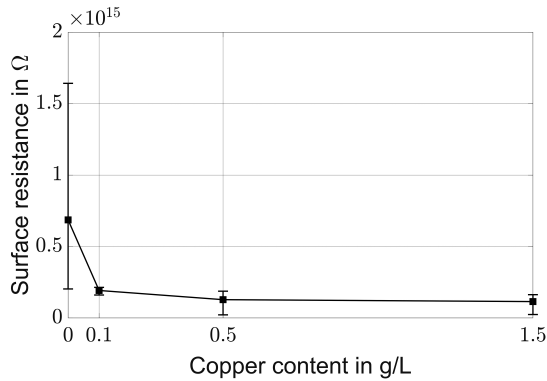


Fig. 12. Influence of copper particle content on the surface resistance of the insulation paper

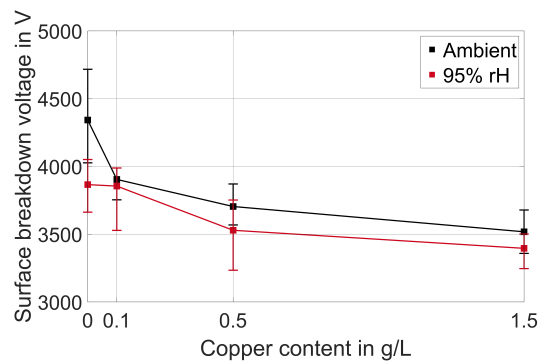


Fig. 13. Influence of copper content and humidity on the surface breakdown voltage of the insulation paper

Besides the effect of conductive particle contaminations, the surface breakdown voltage is measured both at ambient environment and at 95% rH (relative humidity). An increase of the relative humidity results in a decrease of the surface breakdown voltage, as shown in Fig. 13. In accordance with the impact of the contamination grade IV as introduced in Table 1, the humidity acts as a medium for the discrete particle contaminations on the material surface and subsequently increases the surface conductivity.

4. Conclusions

In the present work, particle contaminations of oils in the electrical machine and the transmission system are analyzed. The results show that conductive particles occur during operation of the electric drive train system. Specifically, in the electrical machine, small particles with a size range of 10 nm – 100 nm are dominant, while in the transmission system, larger particles ranging from nanometer to micrometer are prone to form. Besides, the element composition of the particle contaminations is analyzed. The results show that the particles are mainly composed of iron, in addition, other metallic element such as copper and aluminum are also observed. Through the

particle analysis of the oil, it is evident that the particle contamination of the oils in the electric drive system should be considered during design of the electric drive train system.

Besides, through the experimental study, the influence of oils on the electrical behavior of the insulation materials, such as the occurrence of PD and electrical breakdown, are studied. Results show that the cooling oils act as additional insulation, helping to avoid PDs between the windings. In this case, the insulation materials are prone to breakdown directly by increasing operation voltage, before the PD occurs. For the influence of oil contamination with conductive particles, results show that the occurrence of the PD decreases significantly with increasing particle concentration. The dielectric properties on the surface of the insulation materials also decrease with increasing particle concentration, and the property degradation is more sensitive in the low concentration region than in the relative higher concentration region. The detrimental effect of the conductive particles on the surface of the insulation materials can be strengthened by the humidity.

In the future work, the issue of particle contaminations of the cooling oil should be further and fully studied. On one hand, field oils should be analyzed further to obtain more information about the issue of the oil contamination. On the other hand, experiments about the effect of particle contaminations in the oils should be conducted comprehensively. Generally, not only the electrical influence of the particle contaminations, but also the mechanical and chemical influences on the winding insulation system of the electrical machine. In this way, guidelines can be provided for the design of a cooling system or a new drive system with combined use of oils.

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