Preliminary Study on the Applicability of Water-Based Lubricant as a Direct Cooling Medium in Rotating Electrical Machines

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***Abstract*—Direct oil cooling is particularly popular in modern electric drive systems as it enables an effective cooling performance. Subsequently, the power density of the electric drive can be significantly increased. However, the cooling efficiency is severely limited due to the significantly lower heat capacity and thermal conductivity of oils than the conventional cooling medium, water. To overcome the limitation of oil cooling, a water-based lubricant possessing much higher heat capacity and thermal conductivity is developed as a direct cooling medium. Considering the high electric conductivity, the applicability of the water-based lubricant is discussed in this paper under the aspects of material compatibility and the effects on the electric behavior of the insulation system. The results indicate sufficient material compatibility of the lubricant with the enameled wire. The lubricant affects the insulation system during operation as its presence enhances the likelihood of electric leakage and leads to electric field concentration on the insulation materials.**

***Index Terms*—direct oil cooling, electric drive, water-based lubricant, insulation system, material compatibility**

I. Introduction

The modern design of rotating electrical machines in traction applications aims at increasing the power density of the entire electrical drive train system. An increased power density can be obtained by means of reducing the volume requirement and, at the same time, increasing the output power. The former approach can be obtained with advanced machine topology, and the latter highly relies on thermal management performance. With sufficient cooling performance, the operational limit of the machine can be enhanced significantly [1]. Especially in electric traction drive systems, due to limited installation space and an elevated requirement on the output power, an efficient cooling strategy is essential. Direct oil cooling has gained particular attention in recent decades thanks to its unique cooling performance [2], [3]. In direct cooling technology, the cooling fluid comes in direct contact with the heating sources, leading to a short heat path and, therefore, a low thermal resistance between the coolant and the winding system. A combined application of oils as the coolant for the electrical machine and the lubricant for the transmission system is also possible [4], which helps to reduce the volume requirement. Subsequently, the power density of the drive system can be further increased.

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In the conventional concept of direct oil cooling, the employed oil is required to possess proper dielectric properties and appropriate material compatibility with the inner machine components, since it is directly used in the winding system [5], [6]. However, conventional cooling oil has an apparent drawback: significantly lower heat capacity and thermal conductivity than the traditional indirect cooling fluid, water. Assuming that the advantages of oils and water can be combined into one fluid, the cooling efficiency could be improved significantly. With this assumption, a water-based lubricant (WBL) is developed as a direct cooling medium for electrical machines. The WBL is a continuous liquid composed of synthetic base oil, distilled water, and lubricant additives. Additives can be selected under specific applications. The deliberate introduction of water to the insulation system is unintuitive. However, due to the WBL's large heat capacity and thermal conductivity, a resulting advantage for the cooling performance can be assumed [7]. Considering the variety of available potential insulation materials [8], it is presumable that the insulation system can be toughened for the application of WBLs.

In this study, the material compatibility with the machine components and the electrical response of the insulation system in the WBL environment are examined for the state-of-the-art insulation materials. A fundamental understanding of this issue is obtained with the help of experimental and numerical analyses. Suggestions for the progress of the application of the WBL are given from the viewpoint of electrical machines.

II. Methodology

A. Fluid Properties & Cooling Capability

The heat transfer coefficient h_c is usually calculated to evaluate the thermal performance of coolants during the operation. Non-dimensional numbers are popular in thermal management [9], [10] since they enable to correlate h_c directly to oil properties and machine boundary conditions. The dimensions of the related properties and boundary conditions are listed in TABLE I. Specifically, the Prandtl number Pr in (1) is correlated to the material properties, and the Reynolds number

TABLE I: DIMENSIONS OF RELATED PARAMETERS FOR THE CALCULATION OF NON-DIMENSIONAL NUMBERS.

Symbol	Description	Unit
μ	Fluid dynamic viscosity	$\mathrm{kg/m/s}$
ρ	Fluid density	$\mathrm{kg/m^3}$
λ	Fluid thermal conductivity	$\mathrm{W/m/K}$
c_p	Fluid specific heat capacity	$\mathrm{J/kg/K}$
v	Fluid velocity	$\mathrm{m/s}$
l_c	Characteristic thermal length	m
D	Diameter of a circular duct	m
L	Length of the duct	m

Re in (2) is linked with the dimension of oil flow. The Nusselt number Nu is a function of Pr and Re, as depicted in (3). The heat transfer coefficient h_c can be calculated with Nu, as described in (4):

$$Pr = \frac{\mu c_\mathrm{p}}{\lambda}, \tag{1}$$

$$Re = \frac{\rho v l_\mathrm{c}}{\mu}, \tag{2}$$

$$Nu = f(Re, Pr), \tag{3}$$

$$h_\mathrm{c} = \frac{Nu\lambda}{l_\mathrm{c}}. \tag{4}$$

The characteristic thermal length l_c depends on the geometrical setups. For cooling channels of round shape, the characteristic thermal length l_c corresponds to the diameter of the duct D. The Nusselt number is correlated to a laminar or turbulent flow. Taking laminar flow ($Re < 2300$) for instance, the corresponding Nusselt correlation can be described as [9]:

$$Nu = ({Nu_1}^3 + 0.7^3 + (Nu_2 - 0.7)^3 + {Nu_3}^3)^{1/3}, \tag{5}$$

$$Nu_1 = 3.66, \tag{6}$$

$$Nu_2 = 1.615(Re \cdot Pr\frac{D}{L})^{1/3}, \tag{7}$$

$$Nu_3 = (\frac{2}{1+22Pr})^{1/6}(Re \cdot Pr\frac{D}{L})^{1/2}. \tag{8}$$

To prove the advanced cooling performance of the WBL in comparison to conventional E-fluids, the heat transfer coefficient h_c can be calculated with the Nusselt number Nu according to (4). A commercial automatic transmission fluid (ATF) is used for the comparison. Specifications of the WBL and the ATF are provided in TABLE II. Assuming a laminar flow with defined boundary conditions listed in TABLE III, the resultant h_c for both fluids are calculated according to (1)-(8) and summarized in the same table. The results show that under the same boundary condition, the heat transfer coefficient of the WBL is approximately 2.5 times higher than that of the ATF, proving its significance during application as a direct cooling medium in electrical machines.

TABLE II: SPECIFICATIONS OF THE APPLIED WBL IN COMPARISON TO A COMMERCIAL ATF AT 40 °C [5].

Parameter	WBL	ATF [5]
Viscosity in $\mathrm{mm^2/s}$	24.0	31.3
Density in $\mathrm{kg/m^3}$	1060.0	828.9
Thermal conductivity in $\mathrm{W/(m \cdot K)}$	0.3840	0.1398
Specific heat capacity in $\mathrm{J/(kg \cdot K)}$	3200	2110

TABLE III: COOLING BOUNDARY CONDITIONS AND RESULTANT HEAT TRANSFER COEFFICIENTS OF WBL AND ATF AT 40 °C.

Fluid type	WBL	ATF
Fluid velocity v in $\mathrm{m/s}$	0.85	
Diameter of the duct D in m	0.005	
Length of the duct L in m	1	
Heat transfer coefficient h_c in $\mathrm{W/(m^2 \cdot K)}$	690.5	281.8

B. Experimental Study on Material Compatibility

To study the material compatibility of the WBL with the insulation components, the enameled wire Damid 200, Grade 2 is applied. The insulation coating of the Damid 200 possesses a dual-coating system: polyester-imide (PEI) as the base coating and polyamide-imide (PAI) as the overcoating, with a recognized thermal class of 200 °C. This type of enameled wire is usually used as a standard winding material in electric traction or servo machines. During the experiment, the raw enameled wires are immersed in the WBL and are stored in a sealed heating pot, as demonstrated in Fig. 1. The compatibility is investigated under a relatively high temperature to accelerate possible interactions. However, due to the water content in the fluid, the applied temperature should be limited to 100 °C to avoid boiling. Therefore, in this work, the setup mentioned above is thermally conditioned at 90 °C. The total duration of the thermal conditioning is 1008 h with four sampling points: 24 h, 336 h, 772 h and 1008 h. For comparison, one group of insulation materials is separately conditioned without the presence of any fluid. At the same time, the WBL is also conditioned at the same temperature without being in contact

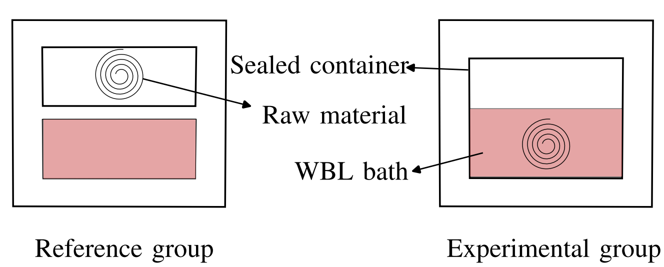


Fig. 1: Setup of thermal conditioning.

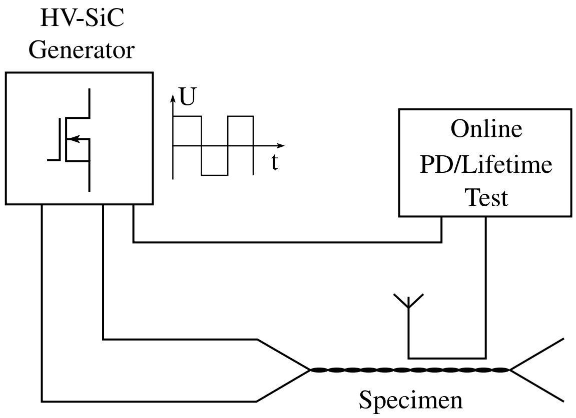


Fig. 2: Schematic of the test bench for PDIV and lifetime tests.

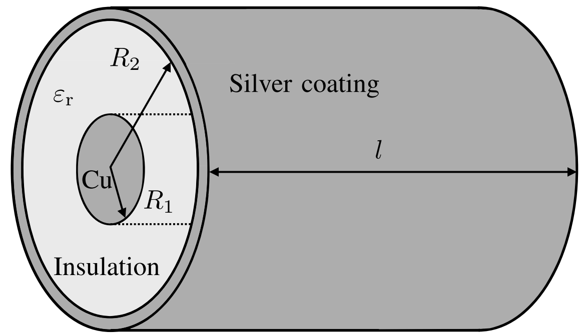
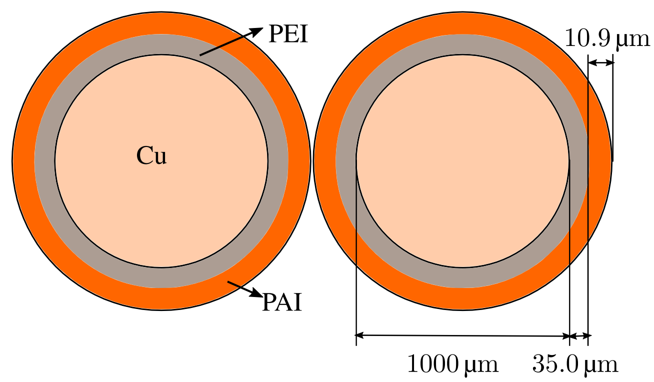


Fig. 3: Demonstration of the single enameled wire as a cylindrical capacitor.



Note: the drawing is not to scale.

Fig. 4: Demonstration of the finite element model of two adjacent round conductors.

with insulation materials. Thus, the effect of aging on material compatibility issues can be studied individually.

To evaluate the material compatibility, various properties of the enameled wire, such as PDIV, capacitance, relative permittivity, and peel strength, are examined at different aging stage. Single wire samples and twisted pairs are produced for the tests of enameled wires. For the twisted pair, the capacitance at $10\,\mathrm{kHz}$ and the partial discharge inception voltage (PDIV) at a switching frequency of 10 kHz are tested with the IEM HV generator [11], with five specimens for each measuring point. A schematic of the test bench for the PDIV tests is shown in Fig. 2.

The relative permittivity of the wire enamel is measured utilizing capacitance measurement with the single wire specimen, as shown in Fig. 3. The silver coating is painted to improve the electric conductivity of the wire surface. Five specimens are applied for each measuring point. With the measured capacitance C, the relative permittivity ε_r of the wire enamel can be expressed with:

$$\varepsilon_\mathrm{r} = \frac{C}{2\pi\varepsilon_0 l}\ln(\frac{R_2}{R_1}). \tag{9}$$

Where R_1 and R_2 are radii of the copper conductor and the enameled wire, l denotes the effective length of the wire, and ε_0 indicates the permittivity in the vacuum space. Details of this measurement technology can be found in [12].

In addition to the dielectric properties, the mechanical properties of the enameled wire are also examined with the peel test. The wire is cut into segments of $1\,\mathrm{m}$. During the test, one end of the wire is fixed, and the other end is rotated on the wire axis with a constant stretch of $25\,\mathrm{N}$ and a rotational speed of $100\,\mathrm{rpm}$. The test comes to an end when the coating peels off.

C. Simulation of the Electrical Field Distribution

Numerical and experimental analyses are performed to study the influence of the WBL on the dielectric response of the insulation system. The finite element analysis (FEA) method is used to simulate the distribution of the electrical field strength between two adjacent round conductors made of Damid 200, grade 2. The geometry of the model is demonstrated in Fig. 4. It is worth noting that the minimum distance between two conductors is set to be $2\,\mu\mathrm{m}$ due to numerical reasons. A voltage potential of $1\,\mathrm{V}$ is applied to the conductors. Different fluids, including air, conventional E-fluid, and water, fill in the gap of the conductors to study the influence of various liquids on the electrical field distribution in the winding system. During the simulation, copper and water are regarded as conductors, and the values of relative permittivity for related materials are summarized in TABLE IV.

D. PDIV Measurement & Electrical Lifetime Estimation

Twisted pairs are employed to study the influence of the WBL on the PDIV and lifetime during electrical aging. Specifically, one group of twisted pairs is made of fresh enameled

TABLE IV: RELATIVE PERMITTIVITY OF APPLIED MATERIALS FOR THE FINITE ELEMENT MODEL.

Material	PAI	PEI	Air	E-fluid
Relative permittivity	4.0 [13]	3.5 [13]	1.0	2.1

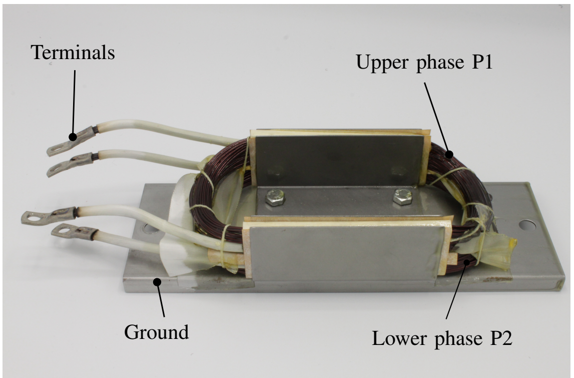


Fig. 5: Setup of the applied motorette.

wire, one group is impregnated with the WBL on the surface of the twisted pair, and another group is impregnated with distilled water for reference. Five samples are used for each group. The lifetime of the twisted pair during electrical aging is estimated with the same setup (see Fig. 2) at a dc-link voltage of $1200\,\mathrm{V}$ and a switching frequency of $10\,\mathrm{kHz}$.

E. Insulation Resistance Measurement

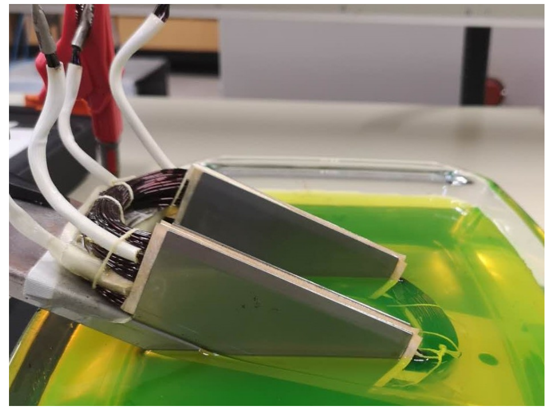
To ensure a healthy operation condition, a minimum insulation resistance between the winding and the stator of $5\,\mathrm{M\Omega}$ is required for a low-voltage winding with round or formed conductors according to the standard IEC 60034-27-4 [14]. The dielectric strength of the insulation system in the WBL environment can be significantly reduced due to the high electrical conductivity of the lubricant. In the present work, two motorettes (M1 & M2) are used as representatives of the insulation system. The configuration of the employed motorettes is provided in Fig. 5. Specifications of the applied motorettes can be found in [15].

The resistances between the two phases and between the phase and the grounded steel sheet, which represents the stator, are measured under different fluid conditions:

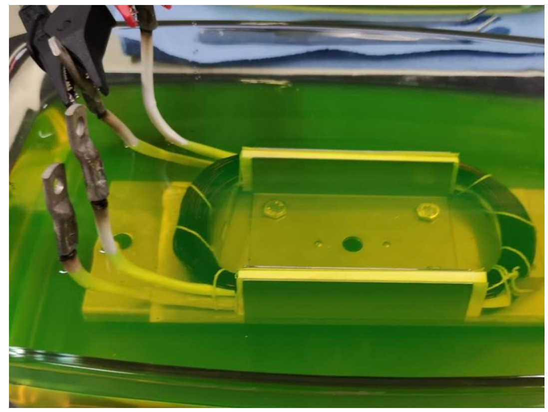
- Reference: fresh motorette in air;
- End-winding wetting: only the end-winding of the motorette is immersed in the fluid (see Fig. 6a);
- Winding wetting: the entire windings are immersed in the fluid, while the phase terminals are dry (see Fig. 6b);
- Complete wetting: the entire windings are immersed in the fluid for $48\,\mathrm{h}$, while the phase terminals are dry.

III. RESULT ANALYSIS

In this section, the material compatibility of the WBL with the enameled wire is evaluated qualitatively and comprehensively with multiple characterization methods. The influence of the WBL on the dielectric strength of the insulation system is analyzed mainly through the PDIV, electrical lifetime and resistance measurements at room temperature. Additionally, the effect of the WBL on the electrical field distribution is analyzed with the finite element methods.



a) End-winding wetting condition.



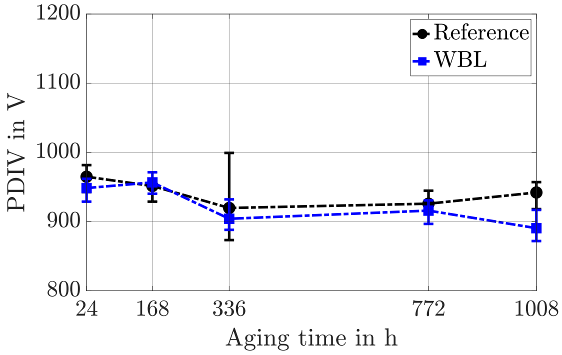
b) Winding wetting condition.

Fig. 6: Resistance measurements at different wetting conditions.

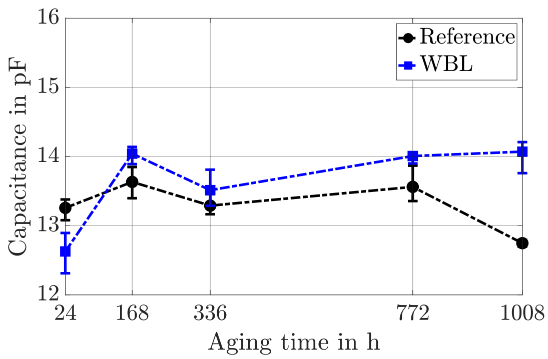
A. Material Compatibility With the Enameled Wire

During the compatibility study, the dielectric properties of the enameled wire are characterized regularly with increasing time of thermal conditioning. As shown in Fig. 7a [16] and Fig. 7b, the PDIV hardly decreases, and the capacitance increases slightly during the conditioning process. Nevertheless, the wire enamel generally possesses good electrical and dielectric properties along the entire period. From this viewpoint, the WBL has sufficient material compatibility with the enameled wire.

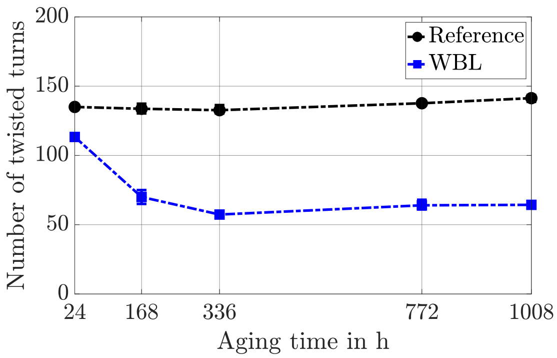
As shown in Fig. 7c, the peel strength of the enameled wire decreases quickly to half of the initial value within $336\,\mathrm{h}$. With increasing conditioning time, the peel strength remains stable until the end of the test. In comparison, the measured results in the reference group stay almost the same as the initial state. The decrease of the peel strength in the WBL group is probably due to fluid penetration into the coating and binding layers. It should be noted that during the preparation of twisted pair specimens according to the standard [17], no mechanical failure is noticed. In a real machine, the twisting stress is usually not critical during the operation, as discussed in [5]. Though the peel test results are not as satisfactory as



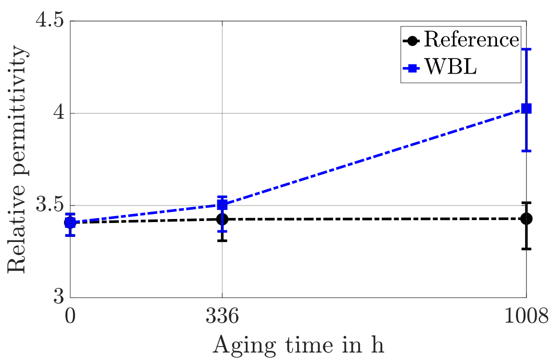
a) PDIV measurement [16].



b) Capacitance measurement.



c) Peel strength measurement.



d) Relative permittivity measurement.

Fig. 7: Influence of the WBL on the dielectric and mechanical properties of the enameled wire with increasing aging time.

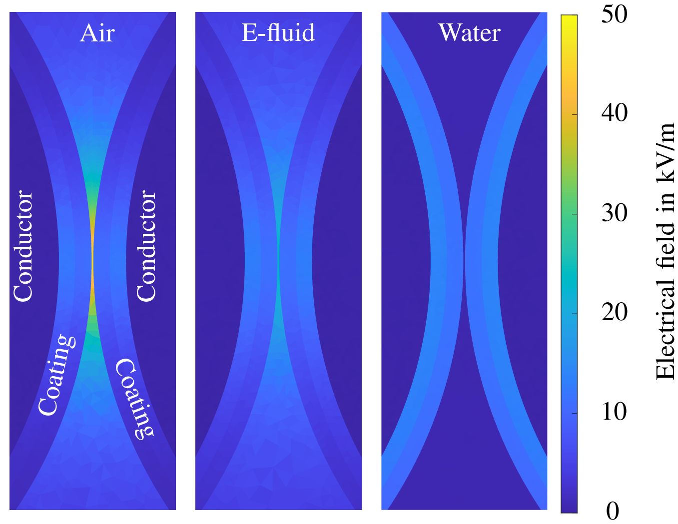


Fig. 8: Electrical field distribution in a twisted pair in different environments.

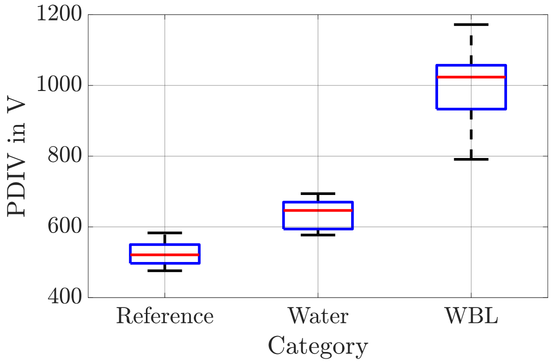
the initial state, it is sufficient for the winding system during the service time.

As shown in Fig. 7d, the relative permittivity of wires conditioned in the WBL at 90 °C increases by approximately 20 % after 1008 h. The reason for a significant increase of the relative permittivity is water absorption of the wire enamel during conditioning in the WBL, due to the high conductivity of water [18], [19].

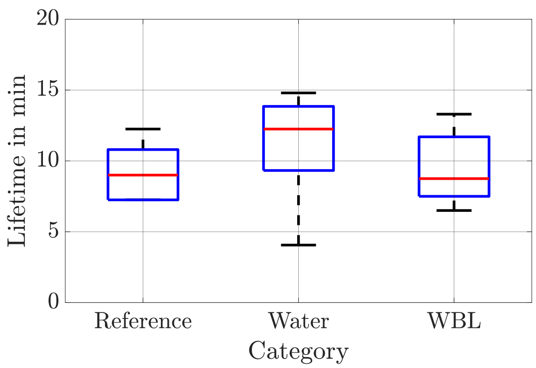
B. Dielectric Strength of the Insulation System

By employing the WBL for cooling purposes, the electrical field distribution in the electrical machine can be significantly influenced. In Fig. 8, there is a comparison of the electrical field distribution between two round conductors in the air, conventional E-fluid, and water environment, respectively. Particularly, water is applied for the worst-case estimation. As depicted in the figure, the electrical field concentrates near the position where the minimum distance occurs in the air. In comparison, the field concentration at this position is significantly weakened in an oil environment due to a relatively higher permittivity of the oil. However, in the water environment, the electrical field concentration happens on the entire insulation coating instead of only at the position where the minimum distance occurs. Applying the WBL makes the insulation coating prone to be electrically stressed. Subsequently, the insulation coating is required to possess a high insulation resistivity.

In addition, the influence of various fluids on the PDIV and electrical lifetime is also studied and compared. As shown in Fig. 9a, the PDIV measurement indicates that the PDIV increases slightly with a water film and significantly with a WBL film on the surface of the twisted pair. Because partial discharge (PD) generally occurs in the gas environment, the fluid film in the gaps of the solid insulation material reduces



a) PDIV measurement.



b) Electrical lifetime.

Fig. 9: Influence of distilled water and WBL on the PDIV and electrical lifetime of twisted pairs.

the risk of PDs. The results of the lifetime estimation in Fig. 9b depict a similar resistance against PDs with different fluids.

For motorettes M1 and M2, the initial resistances between two phases and between one phase and the ground are examined. The resistances ($R_{10\text{s}}$, $R_{60\text{s}}$) are measured at a dc-voltage of $1000\,\text{V}$, which has been applied for $10\,\text{s}$ and $60\,\text{s}$, respectively. Under the drying condition, the measured resistance exceeds the limit of the employed measuring device of $260\,\text{G}\Omega$. Then the resistances at the condition of end-winding wetting are measured, and the results are summarized in TABLE V. For motorette M1, it stays at the gigaohm level. Due to polarization, the resistance value increases with increasing measuring time. However, in motorette M2, the electrical failure between phase P1 and the ground occurs, which is revealed by the low resistance value. It indicates a localized defect between phase P1 and the ground. This defect of the insulation may not lead to machine failure in the normal operation condition without the WBL, as long as the failure part is not in direct contact with other conductive elements. However, it may be detrimental when the WBL is added to the operation environment. Due to the high electrical conductivity of the WBL, a short circuit is formed at this position.

Ensuring that there is no localized failure in motorette M1, it is used for further study. The resistances between two phases of motorette M1 are measured and compared, as summarized in TABLE VI. It shows that the resistances decrease significantly with the increasing wetting area while the polarization indexes (ratio of $R_{60\text{s}}$ / $R_{10\text{s}}$) for the end-winding and winding wetting conditions stay almost the same. After sufficient immersion, the WBL fluid may reach the defect of the inner winding space, and the resistance becomes much smaller than required, as indicated in the resistance measurement at complete wetting. It suggests that any local defect or conductive part is not allowed in the inner space of WBL-cooled electrical machines to avoid short circuits.

TABLE V: RESISTANCE MEASUREMENT UNDER CONDITION OF END-WINDING WETTING.

Component	**Resistance $R_{60\text{s}}$ / $R_{10\text{s}}$ in GΩ**	
	Motorette M1	*Motorette M2*
Phase P1 - ground	37.8 / 16.0	0.9 / 0.05
Phase P2 - ground	21.9 / 12.0	21.5 / 11.5
Phase P1-P2	70.0 / 27.0	21.1 / 15.0

TABLE VI: RESISTANCE MEASUREMENT BETWEEN TWO PHASES OF MOTORETTE M1 UNDER VARIOUS CONDITIONS.

Fluid condition	**Resistance $R_{60\text{s}}$ / $R_{10\text{s}}$ in GΩ**
Reference	$>$ 260 / $>$ 260
End-winding wetting	70.0 / 27.0
Winding wetting	12.5 / 4.9
Complete wetting	0.0009 / 0.0006

IV. Summary and Outlook

In the present work, the applicability of the water-based lubricant WBL is discussed primarily. The applicability is evaluated mainly from the aspects of material compatibility with the insulation system and its response in the WBL environment. The results show that the WBL has sufficient material compatibility with the enameled wire. The electrical field distribution is analyzed numerically. The application of the WBL may result in electric field concentration in the insulation materials due to the high electrical conductivity of the fluid. The PDIV and lifetime of twisted pairs are measured experimentally to evaluate the influence of the WBL on the electrical response of the insulation system. Results show that the WBL film helps to prevent the winding from PDs. Insulation resistances of motorettes are measured under different fluid conditions. The results indicate that direct contact of the WBL with any conductive part of the machine must be avoided. In order to ensure an appropriate application, localized defects must be eliminated by means of either improving the manufacturing quality or taking additional protection measures.

In further work, the material compatibility issues with insulation papers and impregnation materials need to be studied. The advanced cooling performance needs to be verified in specific prototypes of electrical machines. The effect of the WBL on the dielectric strength should be analyzed considering actual machine conditions, and possible improvement of the electrical insulation system for adapting to the WBL working environment is required.

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V. Biographies

Liguo Yang received her M.Sc. degree in material science from RWTH Aachen Univeristy, Germany, in October 2017. Since November 2017 she has been working as a research associate at the Institute of Electrical Machines of RWTH Aachen University. Her research interests include material characterization and lifetime estimation of the insulation system, material compatibility and material ageing in a rotating electrical machine with direct oil cooling.

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Shimin Zhang received his M.Sc. degree in physical-chemistry from ESPCI Paris, France, in June 2016 and M.Eng. degree in energy-related products from IFP-School, France, in June 2018. Since 2018 he has been working as an R&D engineer in the division of Fuel & Lubricant of TotalEnergies OneTech. He works on the fluid and thermal management system for electric mobility.

Hakim El Bahi received his M.Sc. degree in Organic chemistry & Formulation science from ENSCR, France, in 2016 and M.Eng. degree in Energy-related products from IFP School, France, in 2017. Since 2018 he has been working as a research engineer in the R&D division of TotalEnergies, the multi-energy company that produces and markets fuels, lubricants, natural gas and electricity. His research work focuses on the physics of lubrication dedicated to electric vehicles.

Kay Hameyer (IEEE M96 - SM99) received his M.Sc. degree in electrical engineering from the University of Hannover and his Ph.D. degree from the Berlin University of Technology, Germany. After his university studies he worked with the Robert Bosch GmbH in Stuttgart, Germany as a Design Engineer for permanent magnet servo motors and vehicle board net components. From 1996 to 2004 Dr. Hameyer was a full Professor for Numerical Field Computations and Electrical Machines with the KU Leuven in Belgium. Since 2004, he is full Professor and the director of the Institute of Electrical Machines (IEM) at RWTH Aachen University in Germany. In 2006 he was vice dean of the faculty and from 2007 to 2009 he was the dean of the faculty of Electrical Engineering and Information Technology of RWTH Aachen University. His research interests are numerical field computation and optimization, the design and controls of electrical machines, in particular permanent magnet excited machines and induction machines. For several years Dr. Hameyer's work is concerned with magnetically excited audible noise in electrical machines, the life time estimation of insulating systems and the characterization of ferro-magnetic materials. Dr. Hameyer is author of more than 250 journal publications, more than 700 international conference publications and author of 4 books. Dr. Hameyer is a member of VDE, IEEE senior member, fellow of the IET.