The study of the electrical properties of nano insulating oil for submarine cables

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Abstract. At present, the alkylbenzene insulation oil for submarine cables of 220kV and above in China relies on imports, which poses high maintenance costs and supply interruption risks. Nano modified insulating oil has excellent electrical properties and broad application prospects in power systems. Therefore, nano SiO_2 modified insulating oil was prepared, and the effects of APTES modified and unmodified nano SiO_2 on the viscosity, breakdown voltage, and dielectric loss factor of the insulating oil were compared. The results showed that the viscosity of alkylbenzene insulating oil did not change significantly after the addition of nanoparticles, which met the operating standards for submarine cable oil; The breakdown voltage of the modified nano insulating oil has significantly increased, with a breakdown voltage of 0.12g/L being the highest. The breakdown voltage of the unmodified nano insulating oil has significantly decreased. The dielectric loss factors of modified and unmodified nano insulating oils do not vary significantly. This article provides theoretical and practical references for the domestic substitution research of submarine cable insulation oil.

1 Introduction

Submarine cables refer to cables laid on the seabed or riverbed, used to transmit electricity to isolated areas such as islands and offshore drilling platforms. Currently, there are three main types of submarine cables used domestically and internationally: oil-impregnated paper-insulated cables, oil-filled cables, and cross-linked polyethylene (XLPE) insulated cables. For submarine cables with voltages above 500 kV, oil-filled cables are

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used exclusively. Extensive engineering experience has shown that oil-filled cables are more suitable for long-distance, ultra-high voltage, and high-capacity transmission scenarios[1]. The insulation of oil-filled cables is achieved through a combination of solid and liquid insulation, with insulating oil being used to eliminate air gaps formed within the insulation layer, thereby improving the working field strength and providing heat dissipation. Therefore, the performance of the insulation oil is of significant importance to the insulation performance of submarine cables. Dodecylbenzene is a commonly used insulation oil in submarine cables. As oil-filled cables are mainly used in ultra-high voltage environments, there is increasing attention from scholars and engineers to improve their insulation performance[2].

Dodecylbenzene is a monocyclic aromatic hydrocarbon with side chains and is industrially produced through chemical synthesis. It possesses stable electrical and heat dissipation properties, making it widely used in submarine cables. Improving the insulation characteristics of cable oil can prolong the service life of insulation oil and enhance the safety level of submarine cables. With the advancement of nanomaterial research, researchers have gradually realized that a new type of nanodielectric oil can be prepared by adding nanoparticles to transformer insulation oil. Compared to traditional insulation oil, nanodielectric oil not only exhibits superior dielectric performance but also has excellent heat dissipation properties. Nanoparticles have advantages such as small quantum size, small volume, and surface and tunneling effects, providing a reliable method for improving the performance of dielectric insulation materials[3].N.Koutras et al. prepared a natural ester-based TiO_2 nanofluid and tested its electrical properties. The study found that nanofluid samples with different volume fractions of nanoparticles showed varying degrees of improvement in dielectric strength, with the best effect observed at a nanosized TiO_2 content of 0.02%[4]. Yin Xiang investigated the influence of nanosized TiO_2 on the thermal conductivity of insulation oil. The results showed that the thermal conductivity of the nanofluid increased with an increase in the mass fraction of nanosized TiO_2. When the addition amount of nanosized TiO_2 was 1.0%, the thermal conductivity of the nanofluid increased by 8.05%. However, directly incorporating inorganic nanoparticles into the insulation oil is not conducive to enhancing the performance of nanocomposites due to the incompatibility between inorganic additives and organic matrices. Surface modification of nanoparticles can enhance the interface bonding between the nanoparticles and the matrix[5]. ZhangJingWen et al. studied the modification of mineral insulation oil using different surface modifiers and explored the interface properties between nanosized SiO_2 and insulation oil at a microscopic level. It was found that different surface modifiers had varying degrees of influence on the breakdown performance of the nanocomposites in the insulation oil. Among them, the improvement in breakdown voltage was better with APTES surface-modified nanosized SiO_2 compared to HMDS[6].

Therefore, in this study, the surface modification agent amino-propyltriethoxysilane (APTES) was used to modify the surface of nanosized SiO_2, resulting in surface-modified nanosized SiO_2 in alkylbenzene insulation oil. The viscosity, breakdown voltage, and dielectric loss of the modified nanosized SiO_2 alkylbenzene insulation oil and the unmodified SiO_2 alkylbenzene insulation oil were tested at room temperature. The effects of adding modified and unmodified nanosized SiO_2 particles on the electrical properties of the insulation oil were compared.

2. Experimental methods

2.1 Preparation of sample

In this study, domestically produced dodecylbenzene insulating oil is used as the test material, sourced from Jiangsu Tairong Insulation Material Technology Co., Ltd. The basic performance parameters of the insulating oil can be found in Table 1. Externally purchased nano SiO_2 (purchased from McLin Company) is used as an additive, with a particle size ranging from 15 to 20nm, a specific surface area greater than 150, and a purity of at least 99.9%.The surface modifier used is APTES. The hydrolyzable groups on the surface modifier are first subjected to hydrolysis reaction, followed by reaction with the silanol groups on the surface of nano SiO_2 to form silicon-oxygen single bonds. This allows the desired organic groups to be connected to the surface of the nano SiO_2, reducing the hydrophilic hydroxyl groups on the surface and improving its dispersibility in the insulating oil[7].

Table 1. Basic performance parameter of alkylbenzene insulating oil.

Characteristic parameter	Price
Breakdown voltage(kV/2.5mm)	59.7
Kinematic viscosity(40℃, mm²/s)	4.09
Dielectric loss factor(90℃tanδ,50Hz)	0.00073

2.2 Preparation process of nano insulating oil

This study employs a "two-step method" to prepare nano-insulating oil, which involves preparing nano SiO_2 first and then dispersing it into the insulating oil medium.

The nano SiO_2 is modified in the first step. Approximately 1g of SiO_2 powder is added to 20ml of ethanol and subjected to 30 minutes of ultrasonic treatment to form a uniform slurry. About 0.6g of APTES additive is added to the solution, and the mixture is heated at reflux conditions (65°C) for 30 minutes. The solution is then centrifuged, and the precipitate is collected and dried in a 40°C oven, resulting in APTES-modified SiO_2 (A-SiO_2) powder.

The dodecylbenzene oil is vacuum-dried at 90°C for 24 hours to remove moisture and gases from the insulating oil. Using dodecylbenzene oil as the base liquid, the modified nano SiO_2 is added to the base liquid at concentrations of 0.04 g/L, 0.08 g/L, 0.12 g/L, 0.2g/L and 0.3 g/L. The nano SiO_2 is uniformly dispersed in the base liquid using ultrasonic dispersion for 1 hour. To avoid excessive temperature increase caused by continuous ultrasonic dispersion, intermittent ultrasonic dispersion is performed for the nano-modified insulating oil[8].

2.3 Performance testing

2.3.1 Kinematic viscosity

Due to the unique working environment of submarine cable oil, kinematic viscosity is a primary factor to consider. It should not exceed a certain limit (≤6 mm²/s at 40°C) as it can affect its performance. The kinematic viscosity can be tested according to the GB/T 265 standard, which specifies the "Determination of kinematic viscosity of petroleum products and calculation of dynamic viscosity."

2.3.2 Breakdown voltage

The breakdown voltage reflects the insulating oil's electrical endurance and is an important parameter for evaluating its electrical strength. It is also one of the fundamental parameters for assessing the electrical performance of insulating oil. From an operational perspective, it is desirable to maximize the breakdown voltage of the insulating oil. This helps enhance its insulation strength and reduces the quantity of oil required. The breakdown voltage is tested in accordance with the GB/T 507-2002 standard "Determination of breakdown voltage of insulating oils," with a 2.5 mm electrode gap[9].

2.3.3 Dielectric loss factor

The dielectric dissipation factor is one of the parameters that characterize the dielectric performance of insulating oil and is closely related to the structural characteristics of the insulating material. From an operational perspective, it is desirable to minimize the dielectric dissipation factor of the insulating oil. This is because excessive dissipation factor results in excessive active heating, which deteriorates the insulating oil, reduces its insulation performance, and may even lead to breakdown. The dielectric dissipation factor (at 90°C) is tested according to the GB/T 5654-2007 standard "Measurement of relative permittivity, dielectric dissipation factor, and DC resistivity of liquid insulating materials."

3 Results and discussion

3.1 Kinematic viscosity

Generally, as more foreign substances are added, the dynamic viscosity of the insulating oil tends to increase. In this experiment, the maximum concentration of nanoparticles studied is 0.3 g/L. Therefore, the objective is to measure whether the dynamic viscosity of the modified A-SiO_2 and unmodified SiO_2 nano-insulating oils at 40°C, with a concentration of 0.3 g/L, meets the requirement of ≤6 mm^2/s.

According to Table 2, as shown, it can be observed that regardless of the type of nanoparticles added, there is not a significant impact on the viscosity of the insulating oil. This is because the nanoparticles are able to disperse uniformly in the insulating oil without agglomeration or sedimentation, resulting in a relatively small effect on its viscosity.

Table 2. Different nanoparticles affect the Kinematic viscosity of insulating oil.

Kinematic viscosity(mm^2/s)	Price
0	4.09
0.3g/L,A-SiO_2	4.23
0.3g/L,SiO_2	4.77

3.2 Breakdown voltage

Research has shown that adding an appropriate concentration of nanoparticles can improve the AC breakdown voltage of insulating oil. The enhancement in breakdown voltage is influenced by factors such as the concentration, particle size, and surface modification of the nanoparticles. In this study, the AC breakdown voltages of pure oil and insulating oil modified with A-SiO_2 and SiO_2 nanoparticles at concentrations of 0.04, 0.08, 0.12, 0.2, and 0.3 g/L were measured. Each set of samples was tested five times, and the average values were calculated. The results are shown in Figure 1[10].

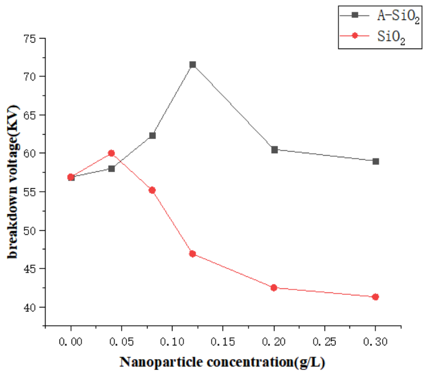

Fig. 1. Breakdown voltage of nanometer insulating oil.

According to the data in Figure 1, the modified A-SiO_2 nano insulating oil has a significant increase in breakdown voltage, and the breakdown voltage continuously increases with the increase of particle concentration. When the nanoparticle is 0.12g/L, the highest breakdown voltage is 71.6KV. The breakdown voltage of unmodified nano insulating oil increases when the concentration is relatively low, but decreases continuously with increasing concentration. This is because it is generally believed that the presence of impurities will reduce the breakdown voltage of insulating oil. However, due to the sub micro scale between meso and micro sizes of nanoparticles, stable sol systems are formed through surface modification or modification of insulating oil. The stable nano insulating oil system not only does not form a small bridge under an external electric field, but the nano effect of the nanoparticles can actually increase the breakdown voltage of transformer oil.

3.3 Dielectric loss factor

The medium loss factor of the nanoparticle-modified insulating oil is shown in Table3. From the data, it can be observed that there is a certain difference in the medium loss factor between the modified and unmodified nanoparticle-insulating oils. The modified nanoparticle-insulating oil exhibits a lower medium loss factor, indicating a certain level of improvement in the medium loss factor due to the modified nanoparticles. However, the difference in the medium loss factor compared to pure oil is very small[11].

Table 3. Dissipation factor of samples (test at 90℃).

A-SiO_2(g/L)	Dielectric loss factor	SiO_2(g/L)	Dielectric loss factor
0.04	0.00059	0.04	0.00074
0.08	0.00027	0.08	0.00066
0.12	0.00021	0.12	0.00031
0.2	0.00038	0.2	0.00559
0.3	0.00035	0.3	0.03799

3.4 Principle of Nano Modification of Insulation Oil

3.4.1 Increasing the insulation strength of insulating oil

Nano-modified particles can form a more uniform and stable insulation layer in the insulating oil. This insulation layer effectively inhibits the accumulation of charges and the concentration of electric fields, thereby enhancing the insulation strength of the insulating oil. The addition of nano particles can fill in the micro-scale defects in the insulating oil, reducing the local amplification of the electric field and increasing the breakdown voltage.

3.4.2 Increasing the dielectric constant of insulating oil

Nano-modified particles have a higher dielectric constant. By dispersing them in the insulating oil, the overall dielectric constant of the oil can be increased. Increasing the dielectric constant of the insulating oil enhances its ability to shield electric fields and reduces the extent of the electric field, thereby increasing the breakdown voltage.

3.4.3 Potential well theory

In insulating oil, charges undergo movement and accumulation under the influence of an electric field, leading to the risk of electric field concentration and breakdown. By adding nanoparticles, these particles disperse in the insulating oil and form potential trap structures. When charges move, they are attracted by and confined within the vicinity of the nanoparticles' potential traps. This potential trap structure effectively suppresses charge accumulation and electric field concentration, thereby enhancing the insulation performance of the insulating oil.

4 Conclusion

This study utilized alkylbenzene insulating oil modified with both unmodified SiO_2 nanoparticles and modified SiO_2 nanoparticles to prepare nanodielectric oils. The researchers tested the dynamic viscosity, breakdown voltage, and dielectric loss factor of the nanodielectric oils. The addition of nanoparticles had little effect on the dynamic viscosity of the alkylbenzene insulating oil. However, the modified nanoparticles significantly increased the breakdown voltage of the insulating oil and also exhibited a certain reduction in the dielectric loss factor. Further research is needed to investigate the influence of temperature on these properties. The research findings reveal the fundamental changes in the electrical performance of nanodielectric oils and have guiding significance for the insulation design and operation of submarine power cables in power systems. They play an important role in practical engineering applications.

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