Elemental Technologies for Ester Oil-immersed Transformers and Reactors

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Abstract

In recent years, demand for environmentally friendly substation equipment has been increasing in Japan. In the transformer field, in particular, the demand for products utilizing ester-based insulating oil has continued to grow.

To meet diverse customer requirements, we have developed oil-immersed transformers using synthetic and natural esters, in addition to conventional modified esters. Before commercialization, we first created a comparison table of the characteristics and key advantages of ester oils. Next, we conducted studies on the insulation and cooling design of ester oil-immersed transformers and reactors, as well as the high-temperature operation of transformers, and evaluated their compatibility of ester oil with transformer component materials. Furthermore, the mixing characteristics were evaluated assuming the use of the same manufacturing equipment. As a result, we expanded our lineup of ester oil-immersed transformers and successfully commercialized ester oil-immersed shunt reactors.

1 Preface

In recent years, the concept of carbon neutrality has gained significant attention in the field of transformers, and the demand for environmentally friendly transformers has increased. The use of biodegradable electrical insulating oil in Japan has expanded rapidly. Ester oils are classified into three types (synthetic esters, natural esters (plant-based oils), and modified esters derived from plant-based oils) according to the JIS C 2390 standard, each with distinct characteristics.

Since 2009, our company has been manufacturing transformers using modified palm fatty acid ester (PFAE)[1]. At that time, the transformer business belonged to Japan AE Power Systems Corporation (2001-2012), a joint venture established and later dissolved by Hitachi, Fuji Electric, and Meiden. This firm specialized in the design, manufacture, and installation of power transmission and distribution equipment, including transformers and gas-insulated switchgear. In response to recent customer demands, now it is expected that we will expand our product lineup to provide customers with a wider choice of ester-based insulating oils. This paper introduces the characteristics and advantages of ester oils, a review of elemental technologies, and the commercialization of ester oil-immersed transformers and reactors.

2 Characteristics of Ester Oils

Table 1 shows a comparative table (representative characteristics) of the characteristics of various insulating oils. The characteristics of three types of ester oils classified by JIS standards are shown, and for reference, the characteristics of mineral oil and silicone oil are also shown.

Synthetic esters have the lowest pour point among ester oils, providing excellent fluidity at low temperatures. In addition, their chemically stable molecular structure gives them superior oxidation stability compared with mineral oil.

Natural esters (plant-based oils), such as soybean oil and rapeseed oil, have higher kinematic viscosity and flash points above 250℃ compared to mineral oil, similar to synthetic esters. Therefore, unlike mineral oil, they are classified as designated flammable materials.

PFAE, a modified ester, is classified as a hazardous material, Class 4, Group 3 petroleum, under the Fire Service Act, the same as mineral oil. It

Table 1 Comparison Table of Characteristics of Various Insulating Oil (Representative Values)

The physical property values of mineral oil, silicone oil, and ester oil conventionally used as insulating oil are shown. The temperature within ( ) of the classification indicates the measured temperature, and (2.5 mm) indicates the length of the gap of the measurement electrode.

Classification item	Units	Mineral oil (reference)	Silicone oil (reference)	Synthetic esters	Natural esters (plant-based oils)		Modified esters
Standards	—	JIS C2320 Type 1 No. 2	JIS C2320 6 types	JIS C2390-1	JIS C2390-2		JIS C2390-3
Appellation	—	Hydrocarbons	Polydimethyl-siloxane	Polyol esters	Soybean oil	Rapeseed oil	Palm Fatty Acid Ester (PFAE)
Density (15℃)	kg/L	0.87	0.96	0.97	0.92	0.92	0.86
Kinematic viscosity (40℃)	mm²/s	8	15	29	32～34	35	5.06
Kinematic viscosity (100℃)	mm²/s	2	7	6	7.7～8.3	8	1.79
Pour point	℃	−32.5	<−60	−56	−18～−21	−30	−37.5
Flash point COC PMCC	℃	148 (COC) —	268 (COC) —	— 260 (PMCC)	320～330 (COC) 260～270 (PMCC)	330 (COC) —	186 (COC) —
Fire point	℃	160	300	316	360	360	206
Acid value	mgKOH/g	0.01	<0.01	<0.03	0.01～0.05	≤0.01	0.005
Breakdown voltage (2.5 mm)	kV	80	70	>75	82	72	81
Dissipation factor (80℃)	%	<0.01	0.01	<0.8 (90℃)	0.54	0.07	0.51
Relative permittivity (80℃)	—	2.2	2.46 (90℃)	3.3	2.9	2.9	2.95
Volume resistivity (80℃)	TΩ·m	35	10	>0.02 (90℃)	0.078	0.5	0.071
Biodegradation rate	% (28th)	—	—	89	100 (EPA)	89	77
Eco Mark certification	—	—	—	—	Certified	Certified	Certified
Hazardous material classification	—	Dangerous goods class 4 class 3 petroleum	Designated combustible materials	Designated combustible materials	Designated combustible materials	Designated combustible materials	Dangerous goods class 4 class 3 petroleum

has the lowest kinematic viscosity among ester oils, resulting in excellent cooling performance. Furthermore, its chemically stable molecular structure provides superior oxidation stability compared with mineral oil.

3 Key Advantages of Ester Oils

Table 2 shows the key advantages of the three types of ester oils classified by JIS standards.

Natural esters (plant-based oils) and modified esters are ester oils made from plant-based oils. Therefore, in the life cycle, including the disposal and incineration process of insulating oil after transformer use, greenhouse gas CO_2 emissions can be reduced compared to products that use petroleum-based mineral oil as insulating oil.

All ester oils are more biodegradable than mineral oil, so the risk of soil contamination in the event of an oil spill is lower than that of mineral oil.

In terms of fire safety, synthetic esters and natural esters (plant-based oils) have a fire point of 300℃ or higher, which is superior to mineral oil. A

Table 2 Appeal Points for Various Ester Oils

The characteristics of synthetic esters, natural esters (plant-based oils), and modified esters are shown.

JIS standards	JIS C2390-1 Synthetic esters	JIS C2390-2 Natural esters (plant-based oils)	JIS C2390-3 Modified esters
Appellation	Polyol esters (MIDEL7131)	Rapeseed and soybean oil (FR3)	PFAE (Pastel NEO)
CO_2 emissions	○	◎	◎
When oil spills No soil contamination	◎	◎	◎
Fire prevention (high incombustibility)	◎	◎	○
Cooling performance	△	△	◎
Oxidative deterioration of oil	◎	○	◎

◎: Superior to mineral oil
○: Equivalent to mineral oil
△: Inferior to mineral oil

notice issued by the Fire and Disaster Management Agency of the Ministry of Internal Affairs and Communications in Japan in March 2023 (Fire Prevention Notice No.205) states that transformers employing natural esters (plant-based oils) with a fire point exceeding 300℃, such as soybean oil and rapeseed oil, can be fitted with large fire extinguishers instead of special fire extinguishing equipment (inert gas fire extinguishing equipment, halogenated hydrocarbon fire extinguishing equipment, or powder fire extinguishing equipment) if certain requirements are met.

Cooling performance is better the lower the kinematic viscosity. Synthetic esters and natural esters (plant-based oils) have higher kinematic viscosity than mineral oils, resulting in inferior cooling performance. However, modified esters have lower kinematic viscosity than mineral oils, resulting in superior cooling performance.

Synthetic esters and modified esters are less susceptible to oxidative degradation of insulating oils than mineral oils because they have a chemically stable structure.

As such, the characteristics differ depending on the type of ester oil, and there is no insulating oil that satisfies all requirements. It is important to select ester oils according to requirements and priorities, such as environmental impact, fire safety, and cooling performance.

The constituent materials used can be directly applied to ester oil-immersed transformers and reactors, as confirmed.

4 Examination of Basic Technologies for Product Commercialization

To commercialize ester oil-immersed transformers and reactors, we examined the insulation, cooling, and material compatibility of the basic design, and evaluated the mixing characteristics of different ester oils, which are necessary when sharing oil treatment facilities during manufacturing.

4.1 Insulation Design and Cooling Design

Using an inter-section model as a composite insulation model for the transformer, we conducted impulse dielectric breakdown tests of ester oils. The test results showed that the insulation performance of synthetic esters, soybean oil, and PFAE were almost the same as those of mineral oil.

Rapeseed oil is a natural ester (plant-based oils) like soybean oil, and since the electrical properties of the oils are almost the same, it was expected that the insulation performance would be almost the same, but the test results were slightly lower. While literature classifies rapeseed oil and soybean oil as the same category, and considers them to have no difference in insulation performance due to the difference in oil type, and to be the same as mineral oil, experimental results allow for insulation design of rapeseed oil that incorporate an appropriate safety margin.

Compared to mineral oil, modified esters have lower kinematic viscosity and superior cooling performance, but synthetic esters and natural esters (plant-based oils) have high kinematic viscosity, resulting in higher pressure loss in the cooling ducts within the windings and the flow paths within the radiators. Therefore, operating temperatures tend to be higher with the same cooling design as for mineral oil. We have established a method for designing cooling according to the physical properties of the oil, extending conventional analysis functions so that the effects of kinematic viscosity are accurately reflected in the calculation of oil flow and temperature distribution.

4.2 High-Temperature Study

Ester oils have a higher water saturation limit than mineral oils, so they absorb moisture from the winding insulation paper and suppress hydrolysis reactions. As a result, it is said that ester oils have a longer insulation life than mineral oils at the same operating temperature. Accordingly, in the temperature rise limits for ester oil/cellulose※1 insulation systems (IEC 60076-14), cellulosic insulators such as kraft paper and pressboard are upgraded from Class A to Class E in ester oil. **Table 3** shows the temperature rise limits, expressed in kelvins (K), for mineral oil (JEC 2200-2014) and ester oil. When mineral oil and kraft paper are used, the maximum oil and winding temperature rise limits are 55 K and 70 K, respectively. When ester oil and thermally upgraded paper are used, however, these limits can be increased to 90 K and 110 K, respectively. Other constituent materials such as gaskets, adhesives, paints, and components can be upgraded to Class E or higher by verifying their thermal performance and replacing them with materials with higher heat resistance as needed.

Table 3 Temperature Rise Limit for Mineral Oil and Ester Oil

The temperature rise limits due to the combination of insulating oil and winding insulating paper are shown. If ester oil is used and winding insulation paper is thermally upgraded paper, the insulation system can be upgraded to thermal class 140℃.

		Mineral oil JEC-2200-2014		Ester oil IEC60076-14	
		Kraft paper	Thermally upgraded paper	Kraft paper	Thermally upgraded paper
Temperature rise limit (K)	Maximum oil	55	60	90	90
	Winding average	55/60※1	65/70※1	75	95
	Highest winding	70	80	90	110

※1. In the case of natural/forced oil circulation

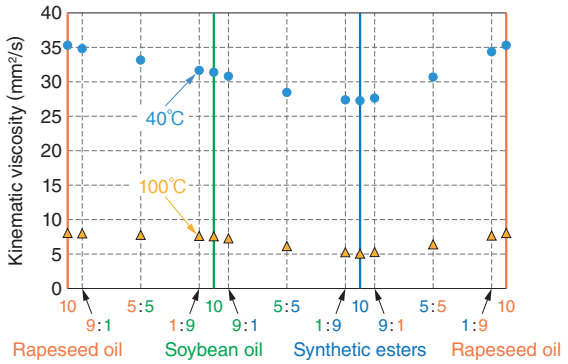

Fig. 1 Mixing Characteristic of High Viscosity Ester Oils (Kinematic Viscosity)

Kinematic viscosity of blended high-viscosity ester oils as a function of mixing ratio. The viscosity changes progressively with the mixing ratio of the constituent ester oils.

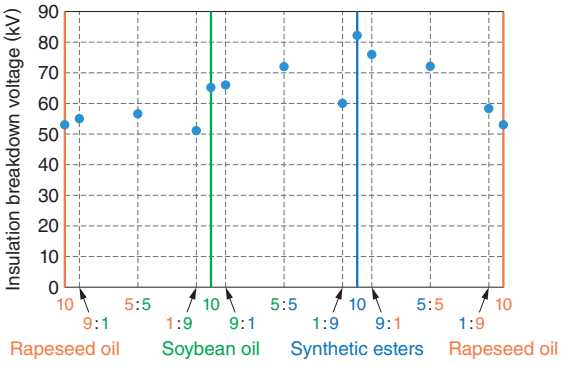

Fig. 2 Mixing Characteristic of High Viscosity Ester Oils (Insulation Breakdown Voltage)

Changes in dielectric breakdown voltage when high-viscosity ester oils are mixed. Although some measurement scatter was observed, the dielectric breakdown voltage generally followed the mixing ratio.

4.3 Compatibility Evaluation of Ester Oil and Materials

This evaluation targeted components and materials already used in mineral oil-immersed transformers and reactors that were suspected of having compatibility issues with ester oil and that come into contact with the oil. The main targets were gaskets, adhesives, and paints. The effects of ester oil were evaluated through analyses of insulating oil properties and dissolved gas characteristics.

The effects on individual components were assessed by examining their individual properties. For example, for gaskets, this involved hardness changes; for adhesives, it involved tensile shear strength; and for paints, it involved adhesion.

The results of the compatibility evaluation showed that the components used in mineral oil-immersed transformers and reactors are generally compatible with ester oil and can be applied without significant issues.

4.4 Mixing Characteristics of High-Viscosity Ester Oils

Although we have been manufacturing PFAE-immersed transformers since 2009, there has been limited experience with high-viscosity ester oils (synthetic esters and natural esters [plant-based oils]). Since the same equipment is used, we use the same equipment for processing the insulating oil used, so there is a possibility of mixing high-viscosity ester oils with each other. To evaluate the mixing characteristics, two of the three types of high-viscosity ester oils – rapeseed oil, soybean oil, and synthetic ester – were mixed at five ratios (0:10, 1:9, 5:5, 9:1, 10:0), and the kinematic viscosity, dielectric breakdown voltage, acid number, and flash point were measured. All test methods conformed to JIS C 2101. Fig. 1 shows the kinematic viscosity, Fig. 2 shows the dielectric breakdown voltage, Fig. 3 shows the acid number, and Fig. 4 shows the flash point measurement results. The horizontal axis of each graph represents the mixing ratio of the two high-viscosity ester oils.

The kinematic viscosity at both 40℃ and 100℃ varied with the mixing ratio and changed progressively between the values of the respective pure high-viscosity ester oils. Dielectric breakdown voltage and acid number also changed according to the mixing ratio, and these changes were generally predictable.

The flash point of synthetic esters was lower

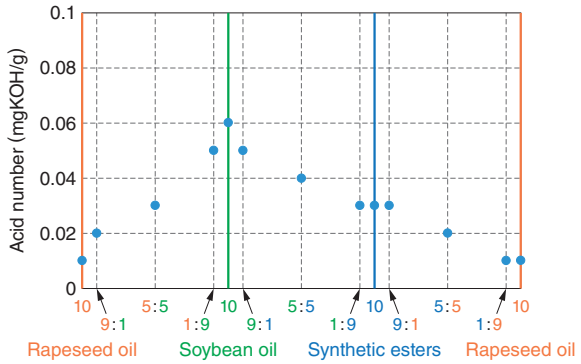

Fig. 3 **Mixing Characteristic of High Viscosity Ester Oils (Acid Number)**

Variation in acid number with the mixing ratio of high-viscosity ester oils. The acid number generally varied according to the mixing ratio of the constituent ester oils.

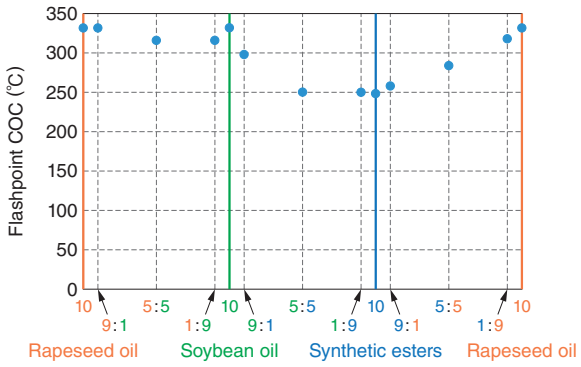

Fig. 4 **Mixing Characteristic (Flash Point) of High Viscosity Ester Oils**

Changes in flash point with the mixing ratio of high-viscosity ester oils. The flash point decreased significantly when synthetic ester was mixed with plant-based oils, exhibiting a greater reduction than expected from the mixing ratio alone.

than that of plant-based oils, and when synthetic esters and plant-based oils were mixed, the flash point tended decrease to a greater extent than would be expected from a simple proportional relationship. In particular, at a synthetic ester: plant-based oils = 5:5 ratio, the flash point became almost as low as that of pure synthetic ester. Since the flash point of natural esters (plant-based oils) is specified as 275℃ or higher in JIS C 2390-2, a synthetic ester:plant-based oils = 5:5 ratio may fail to satisfy this requirement. Therefore, when manufacturing facilities are shared for different high-viscosity ester oils, it is necessary to control the ratio to be within approximately 10%[2]. Furthermore, after mixing high-viscosity ester oils and heating them, the effects on insulating oil properties[3][4] and dissolved gas characteristics were examined, but no significant effects were observed.

5 Realization of Product Development

As a result of studying the fundamental technologies required for the design and manufacture the products described in the previous section, ester oil-immersed transformers and reactors were successfully commercialized.

In June 2023, we expanded our lineup of ester oil-immersed transformers[5], and in May 2024, we issued a press release announcing the commercialization of ester oil-immersed shunt reactors[6]. The main specifications are extra-high-voltage applications and natural oil circulation cooling systems. Furthermore, in November 2024, a press release was issued announcing the supply of ester oil-immersed distribution transformers to TEPCO Power Grid, Inc.[7]

6 Postscript

In recent years, demand has been increasing in Japan for transformers that utilize plant-based esters instead of mineral oil as environmentally friendly substation equipment. Our company has developed the key technologies required for ester oil-immersed transformers and shunt reactors, and has established a product lineup using three types of ester oils (synthetic ester, natural ester (plant-based oils), and plant-based ester) specified in JIS C 2390 Biodegradable Insulating Oil.

Going forward, we intend to propose ester oil-immersed products that meet our customers' needs, by taking advantage of the unique characteristics of each ester oil.

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(Note)

※1. The main component of plant cell walls, and the most abundant carbohydrate on Earth.