Palm Fatty Acid Ester Filled Transformer That Contributes to Reducing Environmental Load

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ABSTRACT

Mineral oil, which has been used as the insulating oil in oil-filled transformers, has problems such as CO_2 emission at the time of disposal and environmental pollution at the time of leakage. On the other hands, vegetable-based insulating oils suffer from a poor cooling effect and low oxidation stability. It is against this backdrop that Fuji Electric, in collaboration with Lion Corporation, developed a palm fatty acid ester (PFAE) with low kinematic viscosity and high oxidation stability through esterification, distillation and purification process of palm oil. Furthermore, Fuji Electric also developed a palm fatty acid ester filled transformer using the PFAE and confirmed that it possesses excellent insulating, cooling, and long-term stability properties. PFAE can be reused as diesel fuel without specific treatment when being disposed, and even if it leaks into the soil, the biodegradation reaction by microorganisms can reduce the impact on the environment.

1. Introduction

To achieve carbon neutrality, in recent years, various industries have demanded products using alternative oil resources. As insulating oil for oil-immersed transformers, mineral oil has commonly been used. However, it has disadvantages, such as CO_2 emissions at the time of burning for disposal and environmental pollution at the time of leakage, and countermeasures are necessary.

It is against this backdrop that Fuji Electric, in collaboration with Lion Corporation, has developed a palm fatty acid ester (PFAE). This material, made from palm oil, has a lower kinematic viscosity and higher oxidation stability than other vegetable oils.

This paper describes a palm fatty acid ester filled transformer that uses PFAE as insulating oil to contribute to reducing environmental loads.

2. Oil-Immersed Transformers

2.1 Overview

The transformer is the equipment that converts the magnitude of AC voltage using the electromagnetic induction phenomena between multiple windings wound around an iron core. They have a history of more than 100 years of industrial use.

Transformers generate hysteresis loss of an iron core and Joule loss of a winding because of their structure. Generally, the conversion efficiency is 99% or more, but as the capacity increases, heat generation due to loss becomes a problem. Therefore, for rated power of several tens of kVA or more, oil-immersed transformers are selected, which use insulating oil as an insulation and cooling medium. Fuji Electric manufactures oil-immersed transformers with rated voltage up to 765 kV and rated power up to 1,100 MVA, which are used in power plants and substations.

2.2 Challenges

(1) Disposal of insulating oil and environmental impact at the time of leakage

Oil-immersed transformers are expected to have a lifetime of approximately 30 years when used under their rated load conditions. For this reason, the following three functions are essential for the insulating oil used as the insulating or cooling medium:

(a) Insulating performance

Insulating oil is used to insulate iron cores, windings, leads and other parts inside transformers. It must secure winding insulation especially against high surge voltages caused by direct lightning or induced lightning to an electric power system.

(b) Cooling performance

Sufficient cooling property is needed to suppress transformer temperature rise due to internal power loss.

(c) Long-term stability

Insulating and cooling characteristics must be maintained without oxidizing deterioration for long-term use.

Mineral oil, which is produced by distilling and refining crude oil, has been widely used as the insulating oil for oil-immersed transformers until now because it satisfies these three essential functions.

On the other hand, it has a disadvantage. To replace or dispose of mineral oil filled transformers, the mineral oil in the tank must be removed and burned, which produces CO_2. In addition, if mineral oil leaks due to deterioration of oil piping packing or an internal failure, it can cause serious environmental pollu-

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tion because it is not biodegradable and may diffuse into and remain in the soil or groundwater for a long period of time. Countermeasures against these problems have become necessary to cope with recent global warming and in terms of environmental conservation.

(2) Size reduction

In the introduction or replacement of oil-immersed transformers, size reduction of equipment is a permanent issue. Size reduction will facilitate user's land utilization, transportation to the site, and installation, enabling users to launch facilities quickly.

3. Palm Fatty Acid Ester Filled Transformer

To solve the issues with mineral oil filled transformers described in Section 2.2, Fuji Electric developed a palm fatty acid ester filled transformer that uses PFAE as an insulation and cooling medium. At present, we manufacture natural convection models with a voltage of 66 / 77 kV and a power of up to 30 MVA.

3.1 Insulating oil (PFAE)

(1) Features

Fuji Electric has developed a vegetable-based oil for transformer insulation as a substitute for mineral oil. As the base oil, we selected palm oil, which is produced in the largest volume among vegetable oils and supplied stably. Because palm oil is highly biodegradable and has no toxicity of chemicals dissolved in water to fish, the environmental impact at the time of leakage is much smaller than mineral oil. However, it has a high kinematic viscosity and is not suitable as an insulating oil for oil-immersed transformers in terms of ensuring the cooling property. We thus have developed a low kinematic viscosity PFAE, which have a molecular structure of saturated fatty acids and be chemically stable and difficult to oxidize, by esterifying (forming ester from acids and alcohols), distillating and refining the palm oil.

Table 1 shows the main characteristics of PFAE in comparison with various insulating oils.

Table 1 Major characteristics of PFAE

Characteristics	Unit	Mineral oil	PFAE	Rape-seed oil	soybean oil
Density (15°C)	kg/L	0.87	0.86	0.92	0.92
Kinematic viscosity (40°C)	mm^2/s	7.7	5.1	35	32.2
Flash point (open type)	°C	150	188	326	326
Flow point	°C	−30	−38	−30	−20
Relative permittivity (80°C)	−	2.2	2.9	2.9	2.9
Dielectric loss tangent (80°C)	%	0.003	0.51	0.05	0.54
Volume resistivity (80°C)	TΩ · m	30	0.13	0.96	0.08
Breakdown voltage (2.5 mm gap)	kV	>80	94	84	82

Features of PFAE as insulating oil are as follows:

(a) Insulating performance

As shown in Table 1, the relative permittivity is higher than that of mineral oil and is close to that of insulating paper as with other vegetable oils. Therefore, the use of PFAE as insulating oil improves the insulation breakdown characteristics.

(b) Cooling performance

Its kinematic viscosity is extremely lower than that of rapeseed oil and soybean oil and is also lower than that of mineral oil, providing excellent cooling properties. Therefore, PFAE is applicable to even large-capacity forced directed insulating liquid circulation transformers.

(c) Long-term stability

When mineral oil is subjected to oxidative degradation treatment (according to JIS C 2101), as shown in Fig. 1, there appear signs of deterioration such as discoloration, generation of black sludge (sinks to the bottom or rises to the oil surface) and increase in the acid value*[1], and the breakdown voltage also decreases.

On the other hand, even after the oxidation degradation treatment, PFAE remains transparent

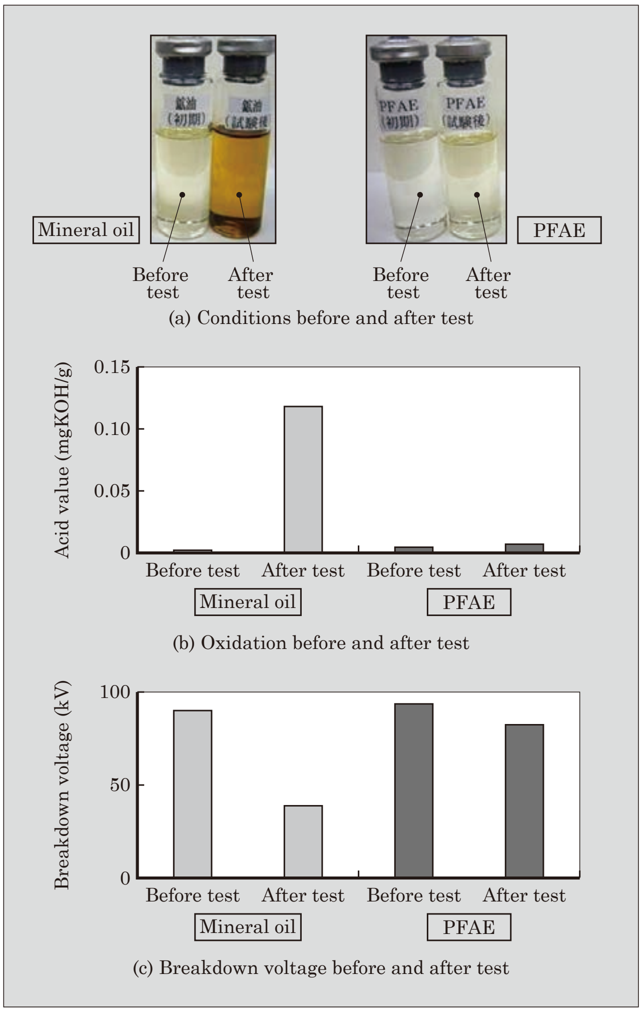


Fig.1 Oxidation stability test results

and shows little increase in the acid value and the breakdown voltage drop. This indicates that the oxidation stability is very high even in the use for a long period of time, and degradation does not easily occur.

(2) Disposal

As described above, the replacement of a mineral oil filled transformer is accompanied by disposing of its oil by burning, generating CO_2. PFAE, meanwhile, is an impurity-free, esterified oil with low kinematic viscosity, which does not require special treatment and is reusable as diesel fuel.

When used as a diesel fuel, it generates CO_2. Nevertheless, it contributes to carbon neutrality because the growing process of palms fixes CO_2 in the atmosphere through photosynthesis.

(3) Environmental impact at the time of leakage

Figure 2 shows the biodegradability of PFAE (according to the OECD Test Guideline 301F). After 28 days, 77% of PFAE degrades and eventually decomposed into water and CO_2 by microorganisms present in the soil.

Regarding fish toxicity (according to JIS K0102), the 96-hour mortality rate is 0% when 10 Japanese killifish are placed in PFAE concentration 100 mg/L, indicating extremely low toxicity.

These features indicate that even if PFAE leaks, its impact on the environment is minimal. PFAE is Eco Mark certified as "biodegradable lubricant version 2.3" (No. 07110003) because it meets the Eco Mark certification criteria for biodegradability and fish toxicity.

We have verified the treatment method in the accident of PFAE leakage based on the oil pollution countermeasures guidelines (for mineral oils). The oil that leaks into the soil is biodegraded by aerobic microorganisms. Even when purification treatment is needed, the inexpensive biosparging method*2 shown in Fig. 3 is applicable at the oil leakage site instead of general excavation and removal.

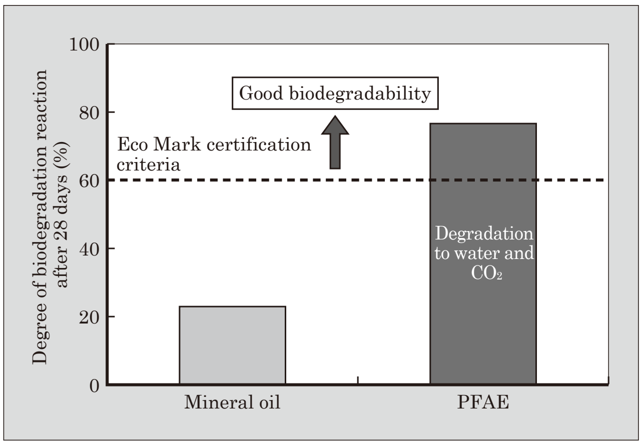


Fig.2 Biodegradability

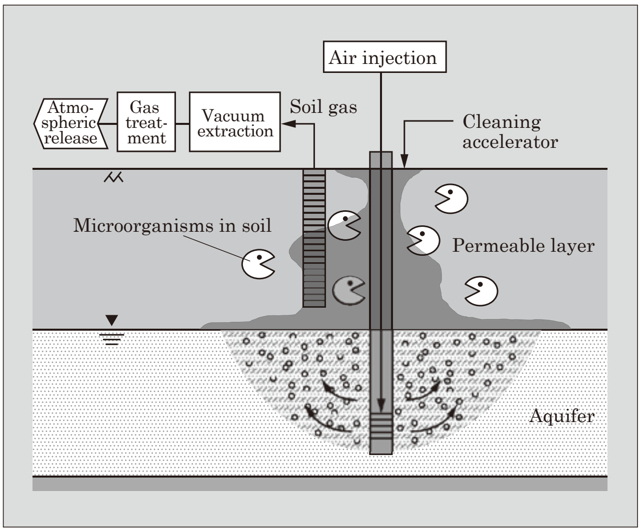


Fig.3 Biosparging method

3.2 Size reduction

Palm fatty acid ester filled transformers can be made more compact than mineral oil filled transformers. For example, when a 6-MVA rectifier transformer is designed with conventional mineral oil (thermal class A) and PFAE (thermal class E), the installation area and the amount of insulating oil of the palm fatty acid ester filled transformer can be reduced to approximately 72% and 60% those of the mineral oil filled transformer respectively. The following describes the reasons for this.

(1) Insulation characteristics

Figure 4 schematically shows the winding structure of a transformer. A kraft paper insulated wire, typically made from copper, is wound concentrically around the iron core. The insulation between the radially adjacent windings is called inter-turn insulation, and the insulation between the sections through the spacer (pressboard) in the vertical direction is called inter-section insulation. We modeled this structure to measure the partial discharge inception voltage when AC and lightning impulse voltages are applied according to the withstand voltage test on transformers (JEC-2200-2014). Table 2 shows the measured results. On the inter-section model in PFAE, the AC and light-

*1 Acid value: An index of the deterioration of fats and oils, which increases with oxidation and hydrolysis. Deterioration progress is accompanied by brownish discoloration and generation of sludge.

*2 Biosparging method: A method to activate aerobic microorganisms in soil and promote biodegradation of oil by laying a pipe that reaches an aquifer at the oil leakage site and injecting air from there. It is applicable to oils with high biodegradability. Depending on the type and concentration of the leakage oil, this method includes the spraying of a purification accelerator to increase the activity of aerobic microorganisms. If necessary, it may also include vacuum extraction of soil gas from the soil, treatment of the gas and release into the atmosphere.

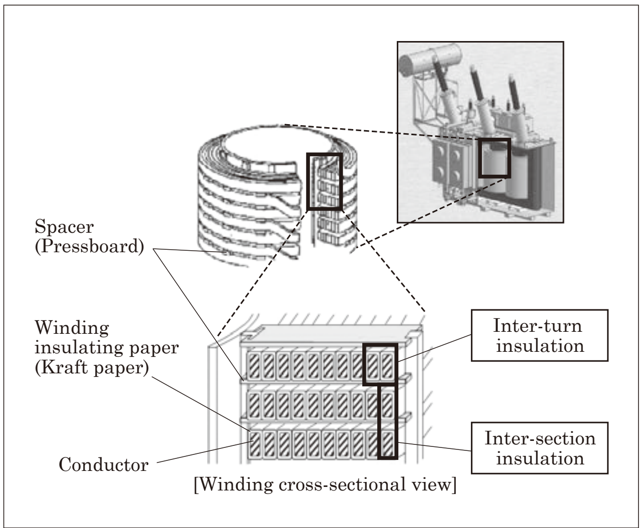
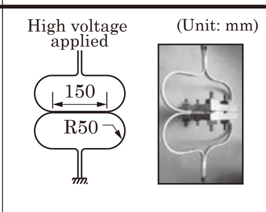
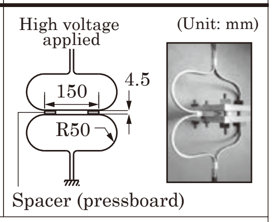
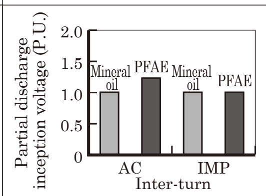
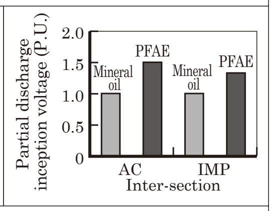


Fig.4 Winding structure of a transformer

Table 2 Measurement results of partial discharge inception voltage of winding model insulation tests

		Inter-turn model	Inter-section model
Test conditions	Model shape		
		Wire used: Insulated rectangular copper wire (3 × 13 mm) wound 0.3-mm thick on each side of the kraft paper	
	Test situation	Immersed in mineral oil or PFAE	
	Applied voltage	AC (50 Hz) : RMS 5-kV (1-minute) step up method IMP (lightning impulse) : Crest value 10-kV step up method	
Evaluation results			
		Inter-section model: Partial discharge starting voltage in PFAE is 1.4 to 1.5 times larger (compared with mineral oil)	

ning impulse partial discharge inception voltages are approximately 1.4 times higher than in mineral oil. This indicates that dielectric breakdown is unlikely to occur, and the palm fatty acid ester filled transformer can have a shorter insulation distance when designed with the same rated voltage and rated power. It thus becomes possible to reduce the amount of insulating oil and to reduce the tank size.

The reason why the insulating property of the palm fatty acid ester filled transformer is particularly high between the sections is explainable using the dielectric constant matching effect.

The insulation breakdown at the winding is caused by the concentration of electric field at the weakest point where the insulating oil, the winding insulating paper and the spacer (pressboard) touch (wedge shaped gap). However, when they have close relative permittivity, permittivity matching effects can work to mitigate concentration of electric field to the wedge shaped gap. The relative permittivity of the PFAE is larger than that of the mineral oil and is closer to those of the winding insulating paper and the pressboard, and the permittivity matching effects mitigate the concentration of electric field to the wedge shaped gap, and electric breakdown is unlikely to occur.

Figure 5 shows equipotential diagrams in intersection models. Focusing on the wedge shaped gap, the number of equipotential lines is smaller and the spacing is wider for PFAE, meaning that the concentration of electric field is mitigated as compared with that in mineral oil.

(2) Cooling characteristics

The kinematic viscosity of PFAE is approximately 0.6 times that of mineral oil, and palm fatty acid ester filled transformers have higher cooling characteristics than mineral oil filled transformers. Using this characteristics, we adopt a high-temperature design with the amount of insulating oil reduced to decrease the tank size. Operation using only a smaller number of coolers also becomes feasible. The details are below.

Figure 6 shows a comparison of cooling characteristics. With respect to the secondary winding temperatures (measured values) with use of PFAE and mineral oil as the insulating oil for a roof delta transformer (with a rated power of 2,000 kVA and a rated voltage of 66 kV) for feeding, the temperature with PEAE was about 1 K lower than mineral oil, and it became 2 K lower as the load factor increased. The heat trans-

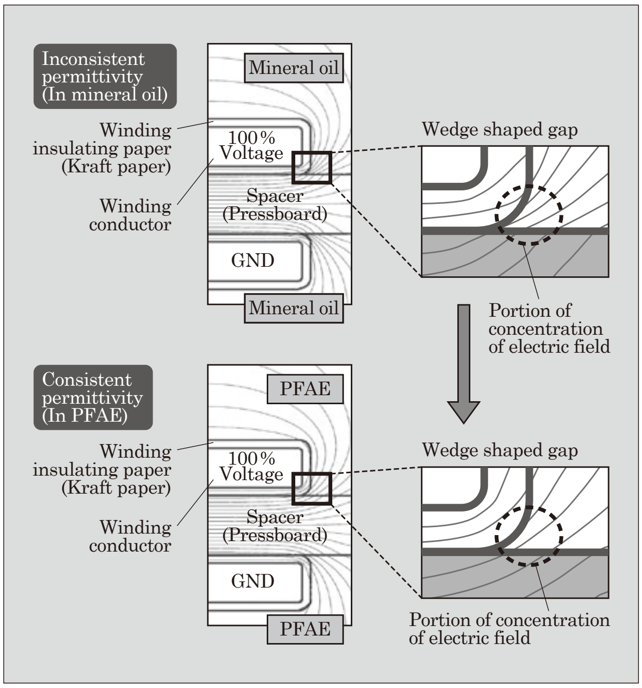


Fig.5 Equipotential diagrams in inter-section models

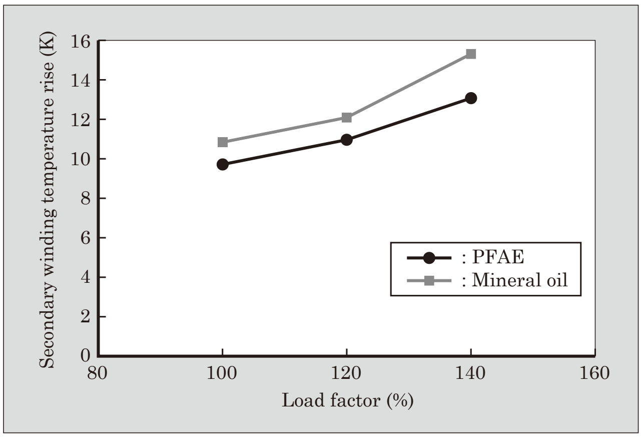


Fig.6 Comparison of cooling characteristics

fer coefficient from the winding to the oil is 1.1 times higher for PFAE than for mineral oil.

In addition, the volume resistivity of PFAE is two orders of magnitude lower than that of mineral oil as shown in Table 1, and PFAE does not contain sulfur, which is a substance causing streaming electrification*3. Therefore, there is little concern about streaming electrification as compared with mineral oil. Eliminating streaming electrification will allow the transformer to increase the circulating flow velocity of the insulating oil to enhance the cooling performance.

Figure 7 shows charging characteristics in pressboard oil duct models. We used the pressboard oil passage in the transformer, in which electric charges tend to accumulate, as a model. As shown in Fig. 7(a), the average values of electric field values were measured at eight points on the model filled with PFAE or mineral oil, and they are plotted against time immediately after the application of voltage. Figure 7(b) shows the electrode shape of the pressboard oil duct model and the eight measurement points.

With PFAE, the electric field value immediately after the voltage application was 1.1 P.U., and the time constant of charge relaxation (time for the electric field value immediately after the voltage application to reach 1/e) attenuated in a short time of approximately 10 s. On the other hand, with mineral oil, the electric field value immediately after the voltage application was 1.6 P.U., which was higher than PFAE. In addition, the time constant of charge relaxation was approximately 3,000 s, which was 300 times larger than that of PFAE.

*3 Streaming electrification: An electrostatic phenomenon in which charge separation occurs between a liquid and a solid surface when the liquid flows on the solid surface. In a large-capacity transformer, when the flow velocity of the insulating oil circulating inside increases, if the charge accumulation in the solid insulator exceeds the in-oil or creeping discharge level, electric discharge occurs inside the transformer, which may lead to destruction of the whole circuit of the winding.

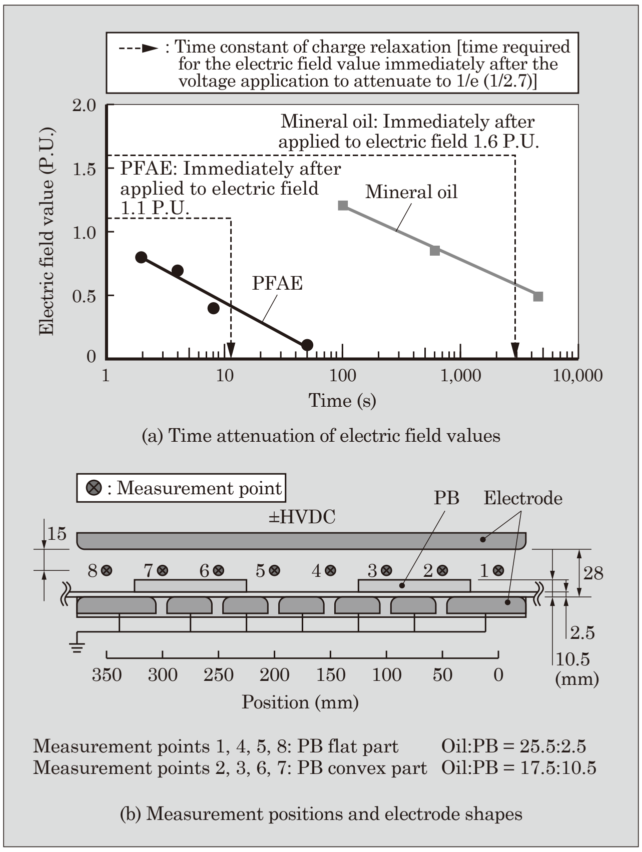


Fig.7 Charging characteristics in pressboard oil duct models

These results demonstrate that streaming electrification is unlikely to occur in palm fatty acid ester filled transformers. Using this properties, we can maintain the cooling performance of the transformer by increasing the circulating flow velocity of the insulating oil even when reducing the amount of the insulating oil or the number of coolers to downsize the equipment.

(3) Lifetime optimization

Cellulose molecules of the insulating paper used inside oil-immersed transformers deteriorate with thermal decomposition and hydrolysis, and the average degree of polymerization (number of monomers constituting the polymer) decreases. When the average degree of polymerization decreased to 45% of the initial state, the winding insulating paper can tear at the generation of short-circuit force due to lightning to the power system, causing interlayer short circuit or ground fault of the winding. When this happens, the transformer has been determined to reach the end of its life.

PFAE, as with other vegetable and silicone oils, has a feature that it has the saturated moisture content that is 1 to 2 orders of magnitude higher than that of mineral oil. When it is used for oil-immersed insulation, moisture on the insulating paper is thus likely to permeate into the oil due to the moisture equilibrium between the insulating paper and the oil, inhibiting the insulating paper from hydrolyzing. As a result, the lifetime of the insulating paper is longer than that

Table 3 Lifetime comparison of thermally upgrade amine paper between PFAE and mineral oil

Deterioration temperature (°C)	151.0	160.0	168.5
(1) In PFAE (h)	1,758	655	265
(2) In mineral oil (h)	758	355	164
Ratio between (1) and (2) [= (1)/(2)]	2.3	1.8	1.6

in mineral oil. Further, PFAE has a higher proportion of saturated fatty acids than other vegetable oils and a very high oxidation stability. It is therefore unlikely to deteriorate in oil characteristics despite the increased moisture in the oil.

Table 3 shows a lifetime comparison between thermally upgrade amine paper immersed in PFAE and in mineral oil. This represents a time when thermally upgrade amine paper (winding insulating paper), which is usable at a temperature 10 K higher than kraft paper, thermally deteriorates in PFAE and mineral oil in a nitrogen atmosphere and the average degree of polymerization decrease to 45%.[1] At the same temperature, the lifetime ratio of the thermally upgrade amine paper in PFAE and in mineral oil is 1.6 to 2.3, and the lifetime of the palm fatty acid ester filled transformer is approximately two times that of the mineral oil filled transformer.

Therefore, adopting the design for downsizing, such as reducing the amount of insulating oil used, and for high temperature operation enables the palm fatty acid ester filled transformer to be downsized while having a sufficient remaining lifetime.

3.3 Abnormality diagnosis technology

When local heating or partial discharge occurs inside a mineral oil filled transformer, mineral oil degrades and in turn produce gas, which dissolves in the oil. Abnormality diagnosis of the transformer can be achieved by analyzing the type and pattern of the dissolved gas.

We confirmed that the main constituent molecules of PFAE are carbon and hydrogen as same as those of mineral oil, and the dissolved gas pattern in the oil generated by local overheating and partial discharge is almost the same as that of mineral oil. Therefore, with the use of the information accumulated for the abnormality diagnosis of a mineral oil transformer, we can perform abnormality diagnosis also for a palm fatty acid ester filled transformer.

3.4 Delivery track records

Since the delivery of the first unit in 2008, Fuji Electric has delivered a total of 175 units, with a total capacity of 328 MVA, to the railway and public sectors, and all the units are operating well. In recent years, we raised the thermal class from the conventional A (105°C) to E (120°C) and advanced size reduction to meet various applications and required specifications.

4. Postscript

This paper described a palm fatty acid ester filled transformer that contributes to reducing environmental loads. The operation track records of palm fatty acid ester filled transformers have increased, and not only laboratory level dessolved gas analysis data[2] but also dessolved gas trends in the actual field are becoming clearer. Measures against global warming are an urgent global issue, and it is expected that the replacement of mineral oil filled transformers, which were introduced in large numbers during the high-growth period, with palm fatty acid ester filled transformers will reduce CO_2 emissions and reduce the installation space for transformers.

Fuji Electric also offers transformers that use natural ester (FR3*4), a high flash point insulating oil, to meet the needs of handling nonhazardous materials, as transformers that contribute to reducing environmental impact.

Fuji Electric will continue to provide environmentally friendly products with high customer satisfaction.

Finally, the Okubo Laboratory at Nagoya University cooperated in evaluating the charging characteristics of the pressboard oil duct shown in Fig. 7. In addition, Lion Corporation, West Japan Railway Company, and Kurita Water Industries Ltd. cooperated in the study of the treatment of PFAE at the time of leakage into the soil. We would like to express our gratitude to all those involved in this research.

*4 FR3: A trademark or registered trademark of Cargill, Incorporated.

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(1) Tokunaga, J. et al. “Lifetime estimation of cellulosic insulation material in palm fatty acid ester for power transformers,” IEEE Trans. DEI. 2017, vol.24, no.2, p.1010–1017.

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