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Study Committee A2

BEYOND THE MINERAL OIL–IMMERSED TRANSFORMER AND REACTORS

Paper 10535_2022

Technological Development of Vegetable Oil (Rapeseed Oil) Immersed Transformer

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1. Motivation

- In Japan, the Japanese Industrial Standards (JIS C2390-1 to -3: 2019) for three types of biodegradable insulating oils, including chemically synthesized ester oils, were published in 2019, the application of vegetable oil based insulating oil to transformers is progressing.

Table. 1 Types of natural ester-based insulating oils and transformer ratings in Japan

Type of cooling insulation liquids		Rapeseed oil	Soy beans oil	PFAE
Number of transformer manufacturers		3	3	7
Ratings (manufactured)	Voltage kV	187	110	77
	Capacity MVA	80	30	40

PFAE :Palm fatty acidester

- As shown in Table. 2, vegetable oil transformers is expanded to the distribution class of electric power companies, it is expected to be applied to high-voltage and large-capacity transformers of transmission classes.

Table 2. Specifications of power transformers to which vegetable oil can be applied

Company	Ratings		Insulating oil specification	Issued
Utility A	Capacity Voltage (Primary / Secondary)	10, 20 and 30 MVA 154, 64.5, 32.25 kV / 6.9kV	use vegetable oil that has the performance as an electrically insulating oil.	2016
	Others	With on load tap changer		
Utility B	Capacity	(unspecified)	Insulating oil for transformers shall be the manufacturer's standard. (Insulating oil was limited to mineral oil, but that limitation was excluded.)	2019
	Voltage (Primary / Secondary / Tertiary)	from 22/6.6 kV to 500/275/77 kV		
	Others	With on load tap changer		
Utility C	Capacity Voltage (Primary / Secondary)	30 MVA or 20 MVA 66 / 6.9 kV or 110 / 22 kV	Whether to use mineral oil or vegetable oil as the insulating oil for the transformer depends on the manufacturer's standards.	2020
	Others	With on load tap changer		

- we will explain the development process, its characteristics, and specific application effects of the rapeseed oil immersed transformer, which is a vegetable oil immersed transformer with a large number of operating units in Japan.

Table 3. Comparison of properties of rapeseed oil and mineral oil

Item		Units	Rapseed oil	Mineral oil
Kinematic vicosity	40 ℃	mm^2/s	38.41	8.31
	100 ℃		8.06	2.21
Flash point		℃	334	144
Fire point		℃	-30	-32.5
Oxidation stability 120 ℃×75 hr		%	0	0.1
		mgKOH/g	0.15	0.2
Permittivity			2.9	2.1
Breakdown strength (water content)		kV/2.5 mm	78 (10 ppm)	70 (10 ppm)
			78 (30 ppm)	55 (30 ppm)
Gas absorbency			-24	-2
Saturated water content		%	Approx.1000	≦100
Sulfur content		ppm	<0.01	0.04
Thermal conductivity		W/(mK)	0.176	0.13
Biograd ability (OECD 301C)		%	89	17

2. Evaluation of Basic Characteristics of Rapeseed Oil

2.1 Oil properties

- Table 3 shows a comparison of the properties of rapeseed oil and mineral oil.
- Rapeseed oil is more oxidatively stable than mineral oil and has a higher kinematic viscosity but a higher thermal conductivity. In addition, it has a high flash point and a high fire point, and is highly safe. It has excellent biodegradability and has cleared the Eco Mark certification standard (60% or more) in biodegradability tests (OECD301C, etc.).

2.2 Insulation characteristics

- As shown in Fig. 1, the saturated water content of rapeseed oil is more than 10 times that of mineral oil, making it easier for paper to absorb water. Even if absorbed, the content in oil is 500 ppm and the breakdown voltage is 60 kV / 2.5 mm.

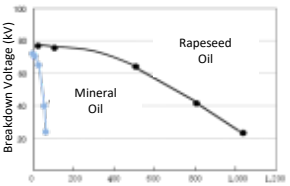
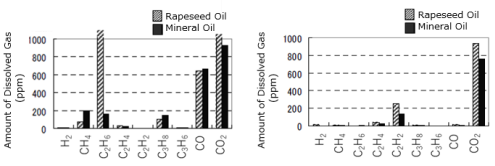


Fig.1 Comparison of dielectric breakdown voltage of rapeseed oil and mineral oil

2.3 Transformer status diagnosis

- Similar to mineral oil-filled transformers, the internal condition of rapeseed oil-filled transformers can be diagnosed by analyzing the combustible gas dissolved in the insulating oil.
- Internal anomalies due to overheating produce more ethane (C2H6) than mineral oil.
- For internal disturbances such as arcing, rapeseed oil and mineral oil have the same gas pattern.



a)Over heart (450℃) b) Arc discharge

Fig.2 Comparison of gas types and amounts generated in rapeseed oil and mineral oil

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2.4 Deterioration characteristics of insulating paper

- Accelerated deterioration tests were conducted in mineral oil and rapeseed oil in order to understand the deterioration characteristics of winding insulation paper in rapeseed oil.
- In this test, insulating paper with an average degree of polymerization residual ratio of 80 % and 65 % was used assuming an aged mineral oil immersed transformer.
- Examples of test results are shown in Figure 3. This verification revealed that the deterioration life of insulating paper in rapeseed oil is more than twice that of mineral oil.

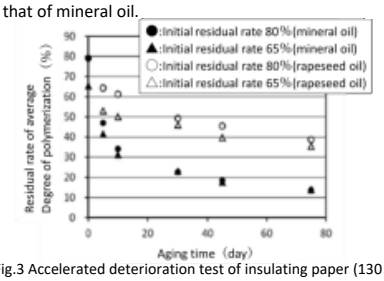

Fig.3 Accelerated deterioration test of insulating paper (130 ℃)

3. Development of Rapeseed Oil Immersed Transformer

- Based on the knowledge obtained from the evaluation of the basic characteristics of rapeseed oil immersed transformer, we carried out energization and load tests using a verifier using a removed mineral oil immersed transformer and a vegetable oil-filled model transformer, and evaluated the performance.

3.1 Verification using the removed mineral oil immersed transformer (three-phase, 10 MVA-66 kV)

- Two units of 10 MVA-66 kV mineral oil transformers with the same rating and 40 years of operation were removed and used as equipment for verifiers.
- In this equipment, to confirm the temperature difference between rapeseed oil and mineral oil, one transformer was immersed with rapeseed oil and the other one was immersed with mineral oil and a circulating current by the tap difference method was passed through the transformer winding as shown in Figure 4.

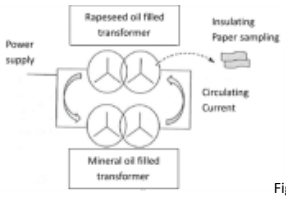

Fig. 4 Experimental equipment conceptual diagram

Fig. 5 Appearance during energization test of 2 Units of three-phase, 10 MVA-66 kV transformer

- The radiator was partially stopped to raise the oil temperature and accelerated deterioration of the insulation.
- The verification test was conducted for about one year, and the equivalent acceleration years calculated from measured temperature such as air, oils and windings were 30 years or more. The appearance of the transformer are shown in Figure 5.
- Table 4 shows the results of measuring the average degree of polymerization of the insulating paper collected before and after the verification test and comparing the relative deterioration aspects.
- The degree of polymerization of insulating paper decreased by 46 % in mineral oil, but decreased by 15 % in rapeseed oil. Similar to the findings of basic characterization, the effect of extending the life of rapeseed oil on mineral oil is expected to be more than doubled.

Table 4 Average degree of polymerization of Winding insulation paper of verification transformer

Types of immersed insulating oil	Average degree of polymerization residual ratio	
	Before energization test	After energization test aging test for equivalent to 30 years
Mineral Oil	100% (initial value)	54 % (▲46 %)
Rapeseed Oil	100% (initial value)	85 % (▲15 %)

3.2 Verification using a model transformer (single-phase, 2 MVA-6.3 kV / 154 kV)

- In order to verify the insulation performance of a 154 kV class rapeseed oil immersed transformer, a model transformer was manufactured and a long-term energization test was conducted.
- Three single-phase transformers with rating 2 MVA and a secondary voltage of 154 kV, were connected to each phase, and each transformer was immersed with rapeseed oil, soybean oil, and palm fatted oil for comparison by insulating oil type of transformer characteristics.

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- An overvoltage applied to the primary voltage of the model transformer, and the accelerated deterioration multiple was calculated from the overvoltage ratio and the long-term V-t characteristics of mineral oil, and the equivalent cumulative years for the test period of 2.08 years was calculated [1].

*Calculation formula for overvoltage multiple [1]

$$\left(\frac{V_1}{V_2}\right) = \left(\frac{L_1}{L_2}\right)^{-\frac{1}{n}}$$

V1: Destruction voltage (kV) corresponding to time t1
V2: Destruction voltage (kV) corresponding to time t2
n: Index indicating the slope of V-t
In this study, n=60 for the general value of oil insulation (long-term region)

- Table 5 shows the overvoltage multiples, acceleration multiples, and cumulative years of the three model transformers.

Table.5 Overvoltage multiple and cumulative period during long-term energization test of 2 MVA-154 kV rated model transformer

Instruments	Transformer 1 (Phase U)	Transformer 2 (Phase U)	Transformer 3 (Phase U)
Type of insulating oil	Rapeseed oil	Soybeans oil	Palm fatty acid ester
Verification test period (years)	2.08	2.08	2.08
Average overvoltage multiple [1]	1.054	1.062	1.055
Average acceleration multiple	28.0	43.4	29.1
Equivalent cumulative period (years)	60.5	94.2	63.1

- Figure 6 shows the appearance of the transformer in the long-term energization test. The verification test period of 2.08 years was equivalent to 60 to 94 years.

Fig. 6 Appearance during long-term energization test of 3 Units of single-phase, 2 MVA-154 kV model transformer

- Figure 7 shows the measurement results of the water content in oil. It shows a gradual increase and decrease tendency depending on the seasonal temperature, which does not depend on the oil type.

- Figure 8 and 9 shows rapeseed oil and soybean oil, which are natural esters, tended to increase in C2H6 and CO, and palm oil, which is a fatty acid ester oil, increased only in CO. The increase in these gases is considered to be due to the deterioration of the insulating oil, and the water content in the oil may affect the deterioration of the insulating oil. measurement results of the water content in oil. It shows a gradual increase and decrease tendency depending on the seasonal temperature, which does not depend on the oil type.

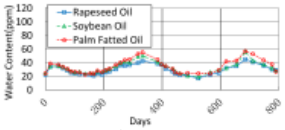

Fig. 7 Trend of water content in oil

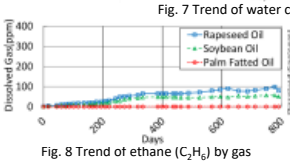

Fig. 8 Trend of ethane (C_2H_6) by gas analysis in oil

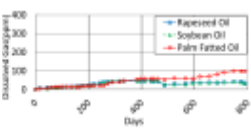

Fig. 9 Trend of carbon monoxide (CO) by gas analysis in oil

4. Conclusion

- We acquired the basic characteristics of rapeseed oil, which affects the insulation, cooling, and deterioration of transformers, and obtained findings that contribute to the deterioration characteristics of insulating paper and rationalization of cooling through long-term tests using a model transformer equivalent to the actual equipment.

- We have reflected them in the transformer design and commercialized, and have supplied more than 400 units by 2020 and are operating without any problems (Figure 10).

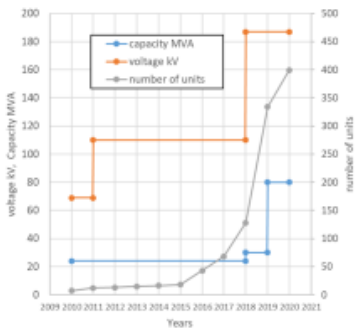

Fig. 10 Trends in voltage and capacity ratings and number of production units of rapeseed oil immersed transformer