A Case Study of Smart Maintenance Applied to 22-77 kV Eco Transformers for Green Transformation (GX)

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Keywords Decarbonization, GX, Transformer, Ester oil, Plant-based oil, Smart maintenance, Operation & maintenance management, Sensor, Continuous remote monitoring

Abstract

Our Numazu Works' Green Transformation (GX) high-voltage substation is a next-generation substation that integrates GX and Digital Transformation (DX). It is constructed with eco-friendly products and incorporates sensors and IoT (Internet of Things) devices to maintain and enhance electrical safety while improving maintenance productivity through smart maintenance practices. The main component, the Eco Transformer, uses plant-based ester oil (non-mineral oil, with the option to select the desired oil type), and by making the transformer specifications an energy-saving type (optional), CO_2 emissions can be reduced. Because the Eco Transformer can accommodate multiple insulating oils, continuous remote monitoring and maintenance management require compatibility with various insulating oils. To address this issue, a hydrogen sensor was applied as a simple means of continuously monitoring hydrogen, one of the gases measured in Dissolved Gas Analysis (DGA). Furthermore, maintenance management standards for various insulating oils were examined.

1 Preface

Addressing climate change and achieving a decarbonized society is a global challenge. Responding to decarbonization has become a crucial management issue for all businesses and organizations in recent years. In Japan, the movement toward decarbonization has accelerated since the Japanese government announced its goal of achieving carbon neutrality by 2050 in October 2020. In recent years, a series of policy measures and institutional frameworks have been introduced, while corporate initiatives have also gained momentum. Furthermore, the Russian invasion of Ukraine in February 2022 has brought renewed attention to the issue of energy security. In response, there is a strong demand to "transform the industrial and social structure, which has been centered on fossil fuels since the Industrial Revolution, to one centered on clean energy, and to transform the entire economic and social system," in other words, to "realize Green Transformation (GX)." In response to this trend, our company is advancing the development of GX products[(1)] and the necessary technologies for the wider adoption. This paper presents a case study of smart maintenance applied to 22-77 kV Eco Transformers for GX products.

2 22-77 kV Eco Transformer in GX Products

Fig. 1 shows an example of smart maintenance application to 22-77 kV Eco Transformers in GX products. GX is attracting attention as it transforms the structure of societies and industries centered on fossil energy into one centered on clean energy. GX is attracting attention not only for addressing climate change problems caused by global warming, but also from the perspective of stable energy supply and revitalizing industrial activities through decarbonization. To meet the diverse needs for environmentally friendly transformers, our company has expanded its lineup of ester oil-immersed transformers[(2)-(5)].

In the field of electrical products maintenance, various challenges exist, including the aging of equipment, the aging and decline of maintenance work personnel, and natural disasters such as

Fig. 1 Eco Transformer for GX High-Voltage Substation

CO_2 emissions can be reduced by using plant-derived ester insulating oil and adopting an energy-efficient transformer design, both of which are available as options. Because Eco Transformers can use various types of insulating oil, continuous monitoring and maintenance management must be compatible with each oil type. To address this issue, a hydrogen sensor was applied to continuously monitor hydrogen, one of the gases measured in dissolved gas analysis. Maintenance management criteria for various insulating oils were also examined.

typhoons. To address these challenges, there is an urgent need to promote and disseminate "smart maintenance," which aims to maintain and improve maintenance levels while simultaneously increasing productivity through the introduction of new technologies such as IoT (Internet of Things), artificial intelligence (AI), and drones[6].

The Smart Maintenance Promotion Committee was established by the National Institute of Technology and Evaluation (NITE) as a forum to confirm and share the validity of new smart maintenance methods utilizing smart maintenance technologies and data. As one of the smart maintenance technology models, our Numazu Works' high-voltage substation[1] was evaluated, and it became possible to significantly reduce the workload of statutory inspections through remote continuous monitoring[6]-[8]. This system aims to reduce the workload required for on-site patrol inspections and the frequency of annual power outage inspections by automating continuous monitoring by installing cameras and various sensors on the substation equipment. On-site walk-around inspections were reduced from once a week to once a month, and annual inspection performed during a scheduled power outage was reduced from once a year to once every six years. Furthermore, trend analysis of monitoring data can help detect early signs of equipment failure and is expected to help prevent equipment problems, including power outages.

The sensors installed in these Eco Transformers in GX products are intended for smart maintenance. Such sensors are required to be applicable to various ester oil-immersed transformers. The TEV (Transient Earth Voltage) sensor used for partial discharge detection[9] is installed on the outside of the tank, so it can be applied regardless of the type of oil. On the other hand, the hydrogen sensor, which simply and continuously monitors only hydrogen gas, a component of Dissolved Gas Analysis (DGA), requires compatibility with various insulating oils, as it involves installing the sensor in different types of oil to detect hydrogen dissolved in that oil.

3 Application of Hydrogen Sensors to Various Insulating Oils

We investigated a hydrogen sensor (ProSense ProGuard 101H), which is one component of a continuous remote monitoring system[10]. While a single-component sensor cannot provide the same level of advanced condition diagnosis as a multi-component sensor, its purpose is to detect signs of abnormalities, such as overheating and discharge, easily and at low cost, and to issue an alarm. High accuracy is not required at this stage; when an alarm is triggered, an oil sample can be taken for high-accuracy dissolved gas analysis (DGA). A feature of the ProGuard 101H is that it detects hydrogen in oil using a fuel cell system, and its internal software processing ensures that the hydrogen concentration remains roughly the same even when the oil temperature changes. While the ProGuard 101H can detect hydrogen in mineral oil, this has not been confirmed with other types of oil.

Therefore, to confirm whether hydrogen can be detected in palm fatty acid ester (PFAE), silicone oil, synthetic esters, soybean oil, and rapeseed oil, the oil temperature and hydrogen concentration in the oil were varied, and the values obtained by quantitative analysis using gas chromatography (GC) were compared with the values measured by a hydrogen sensor. **Table 1** shows the experimental results. When the temperature was changed to 0℃, 30℃, and 60℃, no change was observed in the hydrogen sensor measurements for each insulating oil. As an example, **Fig. 2** shows the measurement results of the hydrogen sensor in hydrogen-dissolved PFAE

Table 1 Hydrogen Sensor Measurement Results when Oil Temperature and Hydrogen Concentration in Oil are Changed for Various Insulating Oils

These results confirm that hydrogen in insulating oils other than mineral oil can also be continuously monitored, indicating that the sensor is a useful monitoring tool for transformers using such oils.

Type of oil	Mineral oil	PFAE	Silicone oil	Synthetic esters	Soybean oil	Rapeseed oil
Temperature dependency	No	No	No	No	No	No
Concentration check (versus GC)	○	○	△	○	○	○
Whether correction is required	No correction required	No correction required	Correction required	No correction required	No correction required	No correction required

○: About the same level as GC, △: Discrepancy with GC

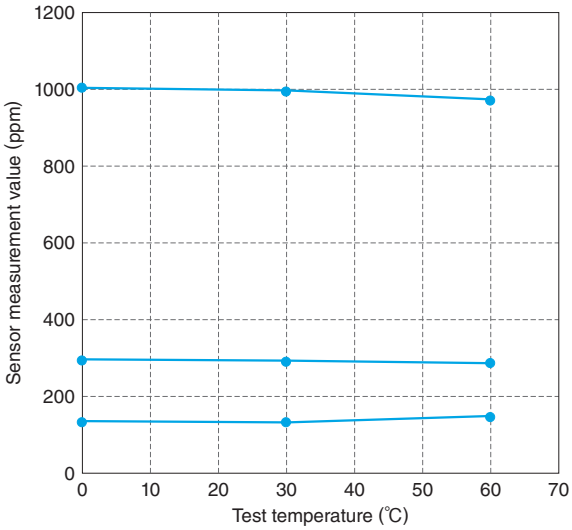

Fig. 2 PFAE Hydrogen Sensor Measurement Results in Hydrogen-Dissolved Oil

The temperature dependency of a hydrogen sensor (example of PFAE) is shown. Owing to the sensor's internal software compensation, changes in oil temperature had little effect on the hydrogen sensor measurements.

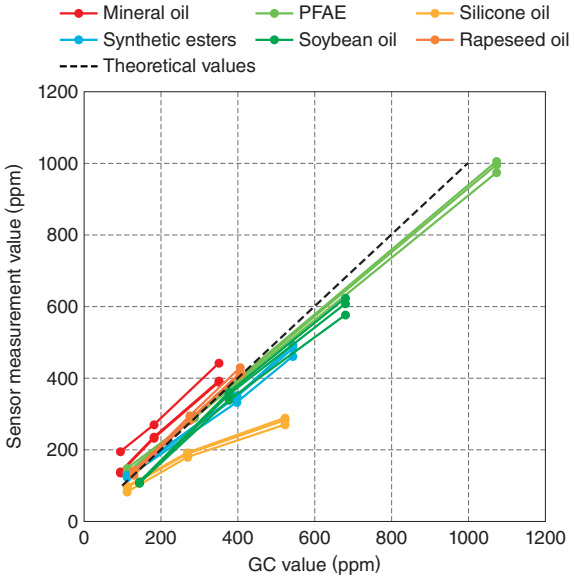

Fig. 3 Relationship between GC and Hydrogen Sensor Measurements at Different Hydrogen Concentrations in Various Insulating Oils

For mineral oil, PFAE, synthetic esters, soybean oil, and rapeseed oil, there was no difference in hydrogen sensor measurement values compared to GC values even when the hydrogen concentration in the oil changed. Since the hydrogen sensor measurement value of silicone oil is smaller than the GC value, it is used by adjusting it with a correction factor.

oil. The test tank was placed in a constant temperature bath, and the temperature conditions were changed to 0℃, 30℃, and 60℃ to confirm the effect of temperature on the hydrogen sensor measurements. After measuring under three temperature conditions at one concentration, the hydrogen-dissolved oil in the test tank was replaced and measurements were taken in the same manner.

Fig. 3 shows the results of confirming the relationship between gas chromatographic analysis and hydrogen sensor measurements when the hydrogen concentration was changed. For mineral oil, PFAE, synthetic esters, soybean oil, and rapeseed oil, the hydrogen sensor measurements agreed well with the GC measurements over the tested range of hydrogen concentrations. For silicone oil, however, the deviation from the GC measurements increased with hydrogen concentration, and the hydrogen sensor indicated lower values. Therefore, a correction factor is required when the sensor is used with silicone oil.

From the above, it can be concluded that the hydrogen sensor is applicable to various insulating oils.

4 Examination of Maintenance and Management Standards for Eco Transformers

DGA is a general method for transformer maintenance and management, and judgment

criteria for mineral oil have been established by organizations such as the Electric Cooperative Research Association (ECRA) and the International Electrotechnical Commission (IEC). Furthermore, previous research[11] examined DGA judgment criteria for PFAE-immersed transformers. Therefore, based on existing mineral oil judgment criteria, we examined DGA judgment criteria for plant-based oils and synthetic esters equivalent to caution levels Ⅰ and Ⅱ and abnormal levels of the Electric Cooperative Research Association (ECRA)[12]-[13].

The results of comparing the gas generation amounts of rapeseed oil and soybean oil with respect to superheating temperature using IEEE Std C57.155 showed that the amount of H_2 gas generated was similar at all temperatures, and the amount of CH_4, C_2H_6, C_2H_4, and CO gas generated was similar at superheating temperatures higher than 450℃. Therefore, the criteria for distinguishing between rapeseed oil and soybean oil as plant-based oils were considered the same. To compare the gas generation amounts of mineral oil with plant-based oils and synthetic esters, the study was conducted based on the results of superheating experiments reported in "Decomposition Gas Behavior during Local Heating of Various Ester-Based Insulating Oils"[14]. Compared to mineral oil, plant-based oils produced approximately 1.8 times more H_2, 1.4 times more CH_4, 4.3 times more C_2H_6, 3.5 times more C_2H_4, and 2.5 times more TCG (total combustible gas). Compared to mineral oil, synthetic esters contained approximately 1.8 times more H_2, 14 times more CH_4, 32.5 times more C_2H_6, 25 times more C_2H_4, and 16 times more TCG. **Table 2** shows the ratios obtained from the test results to the criteria values for caution levels Ⅰ and Ⅱ and abnormal levels for mineral oil. Note that both plant-based oils and synthetic esters were excluded from caution level Ⅰ because of the large amount of CO generated by the decomposition of ester groups. Also, the detection limit for C_2H_2 was set to 0.5 ppm, the same as for mineral oil in gas chromatography. Next, the insulating oil characteristics were examined[15]. In Japan, the maintenance and management of mineral oil-immersed transformers are governed by the Electrical Insulating Oil Maintenance and Management Guidelines, which establish insulating oil management standards before and after operation. For the maintenance and management of synthetic ester and plant-based oil-immersed transformers, international standards are established for insulating oil management before and after operation. However, for plant-derived ester-based PFAE, there are currently no established guidelines or standards for the maintenance and management of insulating oil.

Therefore, we examined the standards for insulating oil maintenance and management before and after operation of PFAE-immersed transformers. In examining the standards for PFAE (sealed

Table 2 Proposed DGA Criteria for Ester-Oil-Immersed Transformers Corresponding to ECRA Caution Levels Ⅰ and Ⅱ and the Abnormal Level

Based on existing DGA criteria for mineral oil, we examined DGA criteria for ester oils corresponding to ECRA Caution Levels Ⅰ and Ⅱ and the Abnormal Level.

(1) Caution Level Ⅰ

	TCG	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO
Mineral oil (ppm)	500	400	100	150	10	0.5	300
PFAE (ppm)	1200	200	160	630	50	0.5	—
Rapeseed oil, soybean oil (ppm)	1200	720	140	640	35	0.5	—
Synthetic esters (ppm)	8000	720	1400	4900	250	0.5	—

(2) Caution Level Ⅱ

Mineral oil	①C_2H_2 ≥ 0.5 ppm	②C_2H_4 ≥ 10 ppm and TCG ≥ 500 ppm
PFAE	①C_2H_2 ≥ 0.5 ppm	②C_2H_4 ≥ 50 ppm and TCG ≥ 1200 ppm
Rapeseed oil, soybean oil	①C_2H_2 ≥ 0.5 ppm	②C_2H_4 ≥ 35 ppm and TCG ≥ 1200 ppm
Synthetic esters	①C_2H_2 ≥ 0.5 ppm	②C_2H_4 ≥ 250 ppm and TCG ≥ 8000 ppm

If either Condition ① or ② is met, the transformer is classified as Caution Level Ⅱ.

(3) Abnormal Level

Mineral oil	①C_2H_2 ≥ 5 ppm	②C_2H_4 ≥ 100 ppm and TCG ≥ 700 ppm
		③C_2H_4 ≥ 100 ppm and TCG increase ≥ 70 ppm/month
PFAE	①C_2H_2 ≥ 5 ppm	②C_2H_4 ≥ 500 ppm and TCG ≥ 1700 ppm
		③C_2H_4 ≥ 500 ppm and TCG increase ≥ 170 ppm/month
Rapeseed oil, soybean oil	①C_2H_2 ≥ 5 ppm	②C_2H_4 ≥ 350 ppm and TCG ≥ 1700 ppm
		③C_2H_4 ≥ 350 ppm and TCG increase ≥ 170 ppm/month
Synthetic esters	①C_2H_2 ≥ 5 ppm	②C_2H_4 ≥ 2500 ppm and TCG ≥ 11,000 ppm
		③C_2H_4 ≥ 2500 ppm and TCG increase ≥ 1100 ppm/month

If any of Conditions ①, ②, or ③ is met, the transformer is classified as being at the Abnormal Level.

Table 3 Results of Examination of Insulating Oil Maintenance Management Standards for PFAE-Immersed Transformers (before Operation)

Insulating oil maintenance management standards before operation of PFAE immersed transformers were examined by referring to electrical insulating oil maintenance management guidelines for mineral oils and international standards for synthetic esters and plant-based oils.
Fill area: standard values specifically referred to during the study

	(Reference)		(Reference)		(Reference)		(Results of the study)
Type of oil	**Mineral oil**		**Synthetic esters**		**Plant-based oil**		**PFAE**
Guidelines/ Standards	**Electrical Insulating Oil Maintenance Management Guidelines in Japan (1983)**		**IEC 61203: 2025**		**IEC 62975: 2021**		—
Test items	**Voltage class**	**Standard values**	**Voltage class**	**Standard values**	**Voltage class**	**Standard values**	**Standard values**
Insulation breakdown voltage (kV/2.5 mm)	11～77 kV	>40	≤72.5 kV	≥55	≤72.5 kV	>55	≥60
	110～275 kV	>50	72.5～170 kV	≥60	72.5～170 kV	>60	
	≥500 kV	>60	>170 kV	≥60	>170 kV	>60	
	Tap changer	>40	Tap changer	(Interpreted as the same as the main body)	Tap changer	(Interpreted as the same as the main body)	≥60
Acid value (mgKOH/g)	11～77 kV	<0.05	≤72.5 kV	≤0.08	≤72.5 kV	<0.08	≤0.05
	110～275 kV	<0.05	72.5～170 kV	≤0.08	72.5～170 kV	<0.08	
	≥500 kV	<0.05	>170 kV	≤0.08	>170 kV	<0.08	
	Tap changer	—	Tap changer	—	Tap changer	—	—
Moisture content (ppm)	11～77 kV	<30	≤72.5 kV	≤200	≤72.5 kV	<200	≤30
	110～275 kV	<15 (275 kV only) <20 (Other than 275 kV)	72.5～170 kV	≤150	72.5～170 kV	<150	
	≥500 kV	<10	>170 kV	≤100	>170 kV	<100	
	Tap changer	<30	Tap changer	—	Tap changer	—	—
Volume resistivity (TΩ·m) (80℃)	11～77 kV	>0.05	≤72.5 kV	—	≤72.5 kV	—	—
	110～275 kV	>0.1	72.5～170 kV		72.5～170 kV		
	≥500kV	>0.1	>170 kV		>170 kV		
	Tap changer	—	Tap changer	—	Tap changer	—	—
Dielectric loss tangent (%) (90℃)	11～77 kV	—	≤72.5 kV	≤10	≤72.5 kV	<7	—
	110～275 kV		72.5～170 kV	≤10	72.5～170 kV	<7	
	≥500 kV		>170 kV	≤10	>170 kV	<7	
	Tap changer	—	Tap changer	—	Tap changer	—	—

body), we referred to the maintenance and management guidelines for mineral oil electrical insulating oil, IEC 61203:2025 for synthetic esters, and IEC 62975:2021 for plant-based oils. **Table 3** shows the standard values for PFAE before operation, and **Table 4** shows the standard values after operation (both in the far right column).

For the PFAE standards, we selected test items (dielectric breakdown voltage of the main body, acid value, water content in the oil, and dielectric breakdown voltage of the tap changer, both before and after operation) that are established in both the mineral oil guidelines and the IEC standards for synthetic esters and plant-based oils. The most important characteristic requiring management for transformer insulating oil is the dielectric breakdown voltage. The insulation properties under the generated electric field are controlled to determine pass/fail judgement, and a standard value can be set regardless of the type of oil. On the other hand, the amount of water in the oil greatly affects the dielectric breakdown voltage and also accelerates the deterioration of the insulating paper. Furthermore, acid value, volume resistivity, and dielectric loss tangent are candidates for control to observe the impact of deterioration products generated by long-term use on the insulating oil. However, it is not always possible to set a standard value regardless of the type of oil. Since test items such as the dielectric breakdown voltage which is the top priority, the amount of water in the oil which greatly affects it, and the acid value which is one of the

Table 4 Results of Examination of Insulating Oil Maintenance Management Standards for PFAE-Immersed Transformers (after Operation)

Insulating oil maintenance management standards after operation of PFAE transformers were examined by referring to electrical insulating oil maintenance management guidelines for mineral oils and international standards for synthetic esters and plant-based oils.
Fill area: standard values specifically referred to during the study

	(Reference)				(Reference)				(Reference)				(Results of the study)
Type of oil	**Mineral oil**				**Synthetic esters**				**Plant-based oil**				**PFAE**
Guidelines/ Standards	**Electrical Insulating Oil Maintenance Management Guidelines in Japan (1983)**				**IEC 61203: 2025**				**IEC 62975: 2021**				—
Test items	**Voltage class**	**Normal**	**Caution**	**Abnormal**	**Voltage class**	**Good**	**Fair**	**Poor**	**Voltage class**	**Good**	**Fair**	**Poor**	**Standard values**
Insulation breakdown voltage (kV/2.5 mm)	11～77 kV	>30	—	<30	≤72.5 kV	>40	30-40	<30	≤72.5 kV	>40	30-40	<30	≥40
	110～275 kV	>40	30-40	<40	72.5～170 kV	>50	40-60	<40	72.5～170 kV	>50	40-60	<40	
	≥500 kV	>50	40-50	<40	>170 kV	>60	50-60	<50	>170 kV	>60	50-60	<50	
	Tap changer	>20	—	≤20	Tap changer (y)	≥30		<30	Tap changer (y)	≥30	<30		≥30
					Tap changer (d)	≥40		<40	Tap changer (d)	≥40	<40		—
Acid value (mgKOH/g)	11～77 kV	<0.2	0.2-0.5	>0.5	≤72.5 kV	<0.5	0.5-1.0	>1.0	≤72.5 kV	<0.30	0.30-0.50	>0.50	≤0.1
	110～275 kV	<0.1	0.1-0.3	>0.3	72.5～170 kV				72.5～170 kV				
	≥500 kV	<0.1	0.1-0.3	>0.3	>170 kV	<0.15	0.15-0.3	>0.3	>170 kV				
	Tap changer	—			Tap changer	—			Tap changer	<0.30	0.30-0.50	>0.50	—
Moisture content (ppm)	11～77 kV	<40	40-50	>50	≤72.5 kV	<200	200-400	>400	≤72.5 kV	<200	200-400	>400	≤40
	110～275 kV	<30	30-40	>40	72.5～170 kV	<150	150-350	>350	72.5～170 kV	<150	150-350	>350	
	≥500 kV	<20	20-30	>30	>170 kV	<100	100-300	>300	>170 kV	<100	100-300	>300	
	Tap changer	—			Tap changer	≤500		>500	Tap changer	≤200	>200		—
Volume resistivity (TΩ·m) (80℃)	11～77 kV	>0.01	0.001-0.01	<0.001	≤72.5 kV	—			≤72.5 kV	—			—
	110～275 kV	>0.01	0.001-0.01	<0.001	72.5～170 kV				72.5～170 kV				
	≥500 kV	>0.05	0.001-0.05	<0.001	>170 kV				>170 kV				
	Tap changer	—			Tap changer	—			Tap changer	—			—
Dielectric loss tangent (%) (90℃)	11～77 kV	—			≤72.5 kV	<15	15-50	>50	≤72.5 kV	<15	15-50	>50	—
	110～275 kV				72.5～170 kV				72.5～170 kV				
	≥500 kV				>170 kV	<15	15-30	>30	>170 kV	<15	15-30	>30	
	Tap changer	—			Tap changer	—			Tap changer	<15	15-50	>50	—

deterioration indicators, although it is not necessarily a sign of a decrease in dielectric breakdown voltage are included, we believe that the combination of test items selected this time is appropriate (it is possible to add items to observe the effects of deterioration, but it is not essential).

For the acceptance criteria before operation shown in **Table 3**, the breakdown voltage of the main transformer insulation was set at ≥60 kV/2.5 mm, the same value specified for mineral oil in the ≥500 kV voltage class, on the assumption that PFAE should provide dielectric strength equivalent to that of mineral oil. The highest criterion was selected with an appropriate margin, without differentiating by voltage class; the same approach was applied to the criteria described below. For the tap changer, taking into account the criteria adopted by overseas manufacturers, the breakdown voltage criterion was also set at ≥60 kV/2.5 mm, the same as that for synthetic esters and plant-based oils. The acid value of the main body was set to ≤0.05 mgKOH/g, the same as mineral oil, since mineral oil and PFAE have similar values before use. While the water content in the main body could be set to the same standard as synthetic esters and plant-based oils, considering the saturated water content, a lower water content is advantageous from the perspective of suppressing transformer degradation over time. Therefore, it was set to ≤30 ppm, which is achievable in our transformer factory's insulation processing process (with a margin of approximately one order of magnitude from the perspective of dielectric breakdown voltage).

Table 4's standard value after operation was set to ≥40 kV/2.5 mm, the same as the abnormal value for mineral oil with a voltage class of ≥500 kV, assuming that the dielectric breakdown voltage of the main body should have the same dielectric strength as mineral oil. The dielectric breakdown voltage of the tap changer (installed at the neutral point of the Y-connection) was set to ≥30 kV/2.5 mm, the same as synthetic esters and plant-based oils, taking into account the standards of overseas manufacturers. The acid value of the main body was set to ≤0.1 mgKOH/g, the same as the normal value, because PFAE has high oxidation stability after use, and is stricter than the abnormal value ≤0.3 mgKOH/g for mineral oil with a voltage class of ≥500 kV. The water content in the oil of the main body was set to ≤40 ppm, 10 ppm higher than before operation, from the perspective of suppressing the deterioration of the transformer over time, similar to before operation (there is a margin of about one order of magnitude from the perspective of dielectric breakdown voltage). Based on the above, we examined DGA (Dissolved Gas Analysis) criteria for various ester oils by applying corrections to existing mineral oil judgment criteria using overheating experiments simulating transformers. Furthermore, we examined insulating oil maintenance management criteria for PFAE-immersed transformers before and after operation, referring to the maintenance management guidelines for mineral insulating oil in Japan and international standards for synthetic esters and plant-based oils.

The above findings are considered the basis for management standard values, and will be reviewed as needed based on future data collection and experiments. In particular, for rapeseed oil and soybean oil, we believe it is necessary to pay close attention to the stray gas phenomenon[16)-18)], where large amounts of C_2H_6 and H_2 are generated during heating in relatively low-temperature ranges, even without overheating or discharge abnormalities.

5 Postscript

We introduced examples of smart maintenance applications for 22-77 kV Eco Transformers in GX products and explained the continuous remote monitoring and the maintenance management that supports them.

Going forward, we intend to promote the widespread adoption of GX products, further advance smart maintenance of electrical equipment, and thereby contribute to decarbonization and GX.

・All product and company names mentioned in this paper are the trademarks and/or service marks of their respective owners.

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