Paper No: 107
A3/B3 Colloquium 2023
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Substation design with compactly developed equipment to reduce carbon footprint

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SUMMARY

The SF_6 alternative gas insulated switchgear and the vegetable insulating oil transformer are introduced to the authors' substation aiming reduction of the carbon footprint [1]. Our experience is reported for the performance of SF_6 alternative GCB and vegetable oil transformer that minimize their footprint. The improved 84kV SF_6 alternative gas circuit breaker is developed with a vacuum interrupter and synthetic air insulation. Compared to conventional SF_6 GCBs, CO_2 is reduced approximately by 350 tons per unit. Air insulating design pressure is increased to enhance dielectric performance, and its enclosure diameter is accordingly minimized. Such design achieves to reuse the existing foundation to replace GCB. The 77kV vegetable oil transformer uses rapeseed oil, a natural ester oil. The vegetable oil also contributes to the reduction of carbon footprint. In addition, the temperature rise limits of the transformer windings and oil are optimized by 10K, which reduces the radiators, and then the transformer is designed compact to enable reusing existing foundation.

KEYWORDS

SF_6 alternative gas, Synthetic air insulation, Vacuum circuit breaker, Rapeseed oil transformers, Upgraded temperature rise limits

1 Introduction

Global efforts are rapidly accelerating towards achieving carbon neutrality in 2050. In Europe and United States, regulations on SF_6 gas are taking shape and SF_6 alternative gas switchgears are being introduced. For transformers, the environmental performance and disaster resistance of natural ester oil have attracted attention and the natural ester transformers are being installed worldwide.

Authors are promoting to introduce SF_6 alternative gas switchgears and transformers with natural ester oil for the substations that achieve a reduction in carbon footprint.

As part of this, 77kV rapeseed oil transformers were adopted as all five transformers of the new substation that started operation in March 2023, and an improved 84kV vacuum circuit breaker (VCB) with synthetic air insulation is adopted in April 2023. Fig. 1 shows the substation using rapeseed oil transformers. In this paper, our experience on introduction of the substation equipment is reported, aiming at carbon footprint reduction. As it is important for utilities that the equipment needs to be installed in the limited area, the experience is described to minimize the equipment size on the synthetic air VCBs and the transformers evaluating its characteristic of rapeseed oil.

Fig.1 Substation applying transformers with rapeseed oil

2 Substation applying environmentally friendly equipment

In October 2020, the Prime Minister of Japan declared to aim for "carbon neutrality in 2050", and Japanese electric power utilities are also promoting measures for decarbonization.

In Japan, many equipment installed during the period of high economic growth around 1970 has reached the time for replacement. Many substations in Japan have limited area for replacement and the equipment is required to be the same or smaller than the existing one. In addition, since disasters such as earthquakes and typhoons have frequently occurred in recent years, environmental impact reduction is required by SF_6 gas or insulation oil leakage. The circuit breakers and transformers have been developed and are introduced to address these issues. The application of these devices in substations can contribute to the reduction of the substations carbon footprint.

In the case of the typical 77kV distribution substation, CO_2 emissions reduction amount for the entire substation is estimated at approximately 780 tons. Also, for the equipment layout, since the substation design can be almost same as before, such design eliminates the need for additional foundation and other relevant works.

3 Improved Vacuum Circuit Breaker with synthetic air insulation

3.1 Ratings and fundamental performance

Table 1 shows the ratings of the newly developed VCB. The arc extinguishing chamber of the circuit breaker uses a vacuum valve that does not generate decomposition gas by current interruption. Synthetic air, a natural gas with zero GWP, is used as the insulating medium since it is harmless for human, and it can be easily handled compared to other alternative gases.

The rated current is covered up to 2000A by improving the heat dissipation of the current-carrying conductors. It is also designed to withstand chopped wave impulse voltage according to IEEE C37.04, that is more severe than the withstand voltage specified in JEC-2390 (Standard by Japanese Electrotechnical Committee) [2].

The operating device is a maintenance-free spring-operated mechanism that does not require greasing. As the vacuum valve has a lower contact wear for load current switching, the VCB is expected to have current switching capability up to 10,000 operating times without inspection. Thus, its inspection interval is extended, and it reduces maintenance work.

Table 1. Ratings of the VCB

Rated Voltage		72/84 kV
Rated Current		2000 A
Rated Short-time Withstand Current		31.5 kA, 3sec
Rated Lightning Impulse Voltage		400kV
Rated Chopped Wave Impulse Withstand Voltage		452kV
Rated Short Circuit Breaking Current		31.5kA
Standard Air Filling pressure	Main chamber	0.9 Mpa abs.
	Lower pressure chamber	0.29 Mpa abs.

3.2 Design and features

Fig. 2 shows the relation between filling air pressure and VCB enclosure diameter. As dielectric strength of air is lower than that of SF_6 gas, VCB enclosure diameter become larger than that of SF_6 GCB accordingly.

To minimize the enclosure diameter, standard air filling pressure is set higher (0.9 MPa-abs) than that of conventional GCB (0.6 MPa-abs) to improve insulation strength. As shown in Fig. 3, the moving part is designed at a lower functional pressure (0.29 MPa-abs) than that on the enclosure side to ensure its mechanical endurance. Though the VCB enclosure diameter is larger than that of the conventional GCB, that has impact on the equipment footprint as well as dead weight and seismic load on the foundation, physical arrangement of primary part is designed to set its footprint to be the same as that of the conventional GCB. Table 2 and Fig. 4 show the comparison for foundation design factors between GCB and VCB. Applying composite bushings to VCB, whereas conventional GCB has porcelain bushings, the dead weight is reduced to 85% of the GCB weight and the moment by seismic load is also reduced to 85%. These enable to reuse of the existing foundation. Compared to the existing GCB, VCB is expected to improve the seismic performance. VCB can withstand conditions 1.5 times more severe condition than the high-level seismic condition specified in IEEE 693 [3][4]. By using synthetic air, the VCB is expected to reduce CO_2 emissions by approximately 350 tons per unit compared to SF_6 GCB.

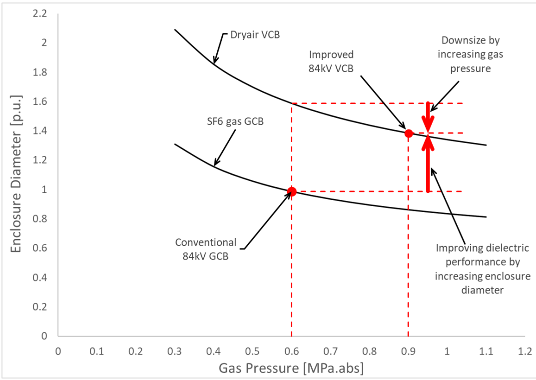

Fig.2 Impact of air pressure on enclosure size

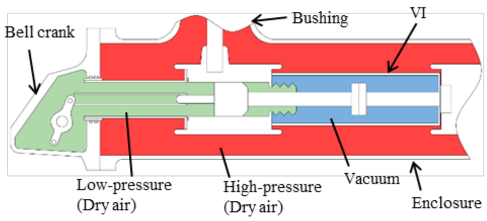

Fig.3 Cross section of 72/84 kV VCB

Table 2. Foundation design comparison between GCB and VCB

	GCB	VCB
Width	100%	107%
Height	100%	100%
Footprint(a-b)	100%-100%	110%-120%
CB weight	100%	85%
Moment by seismic load	100%	85%

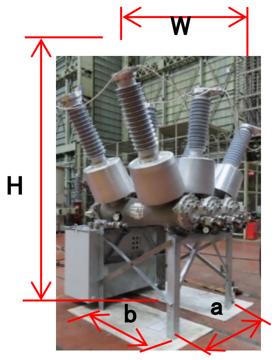

Fig. 4 72/84 kV Improved VCB

4 Natural Ester Oil Transformers

4.1 Overview of Natural Ester Oil (Rapeseed Oil) Transformers

Table 3 shows the transformer specifications applied to the new substation that operation has started in March 2023.

Table 3. Specification of the transformer

Rated voltage	75.25/6.3 kV	73.5/22 kV
Rated capacity	18.26 MVA	30 MVA
Oil type	Rapeseed oil (natural ester)	
Cooling method	KNAN	
Temperature rise limit	Winding: 75 K Oil: 70 K	

Table 4 shows a comparison of ester-based insulating oil properties. The data in Table 3 are based on Bibliography [5][6][7] and the result of measurement by Kansai Transmission and Distribution group company based on tests OECD 301 C. As well as soy oil, rapeseed oil has a high flash point and can contribute to improving the disaster prevention at substations. In addition, rapeseed oil is exempted from hazardous materials under Japan's Fire Service Law. While it is necessary to obtain approval from the fire department chief when temporarily handling mineral oil during construction, no such procedure is required for rapeseed oil. Adopting rapeseed oil as the insulating oil for transformers can reduce CO_2 emissions by about 1/6 over the entire life cycle from growing the raw material oilseed rape to incineration (CO_2 emissions reduction per rapeseed oil transformer: about 26.5 tons).

Rapeseed oil has a higher saturated water content than mineral oil and absorbs it in the insulating paper, thus inhibiting hydrolysis of the insulating paper. It is highly biodegradable, reducing the environmental impact of oil leakage. In addition, rapeseed oil is manufactured in Japan and has a stable supply system.

Table 4. Properties of Ester-based Insulating Oils [5][6][7]

Classification		Natural esters		Synthetic ester	Mineral oil
		Rapeseed oil	Soy oil		
Flash point (COC)	°C	322	330	268	148
Fire point (COC)	°C	360	360	314	160
Kinematic viscosity	$mm^2/s(40°C)$	35	34	31.07	8
	$mm^2/s(100°C)$	8	8	5.676	2
Biodegradability	% (28 days)	89	100	60	17
Water saturation at ambient	mg/kg	1100		2600	55

4.2 Challenges and Solutions in the Application of Rapeseed Oil Transformers

In the case that rapeseed oil is used as the insulating oil in the transformer instead of mineral oil without design change, the difference between the upper and lower oil temperatures during operation increases compared to mineral oil transformers since the oil flow velocity into the winding and radiator slows down. The oil temperature in the upper part of the transformer may exceed the temperature rise limit stipulated in JEC-2200-2014 and it was necessary to increase the number of radiators. For the temperature rise limit in the standard above, the winding temperature and oil temperature rise limits were upgraded by 10K so that transformer costs would be lower. By applying IEC60076-14 for the temperature rise limit of the transformer, the number of radiators was reduced whose physical arrangement is shown in Fig. 5. Hence the transformer can be smaller than the mineral oil-filled transformer. This made it possible to reduce the foundation size of the transformer.

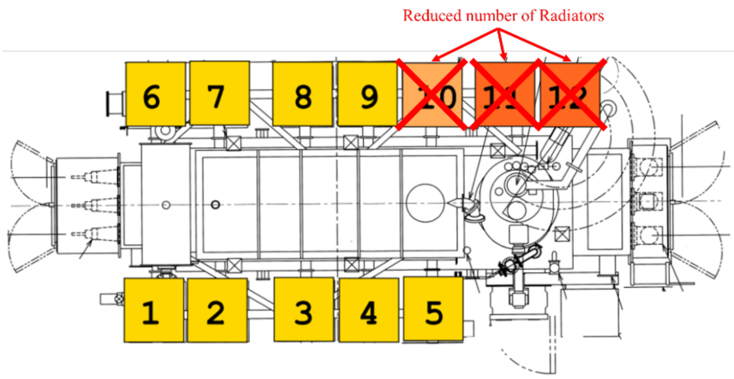

Fig. 5 77/6.6kV 18.26MVA Radiator arrangement of rapeseed oil Transformer

Fig. 6 shows the test results of the insulating paper accelerated degradation, in which insulating paper (thermally upgraded paper) was placed in insulating oil. The dotted line in the graph indicates the average degree of polymerization 450, and the area overlapping the dotted line is the life of the transformer, respectively. The life of the thermally upgraded paper in rapeseed oil is more than 60 years, which is expected to be longer than that of mineral oil transformers, under the same temperature conditions. Fig. 7 and 8 show the relation between the natural logarithm of the reaction rate (κ) and the inverse of the absolute temperature (Arrhenius plot) for the degradation of insulation paper. From the regression lines shown in Fig. 7 and 8, the reaction rates of each oil type and insulation paper are obtained when using of mineral oil/kraft paper at 110°C. Fig. 9 shows the temperature difference at which reaction rate become the same [8]. From Fig. 9, in the case of thermally upgraded paper in the rapeseed oil, a lifetime can be expected equivalent to that of mineral oil even when the temperature rise limit of the transformer is upgraded by 10K.

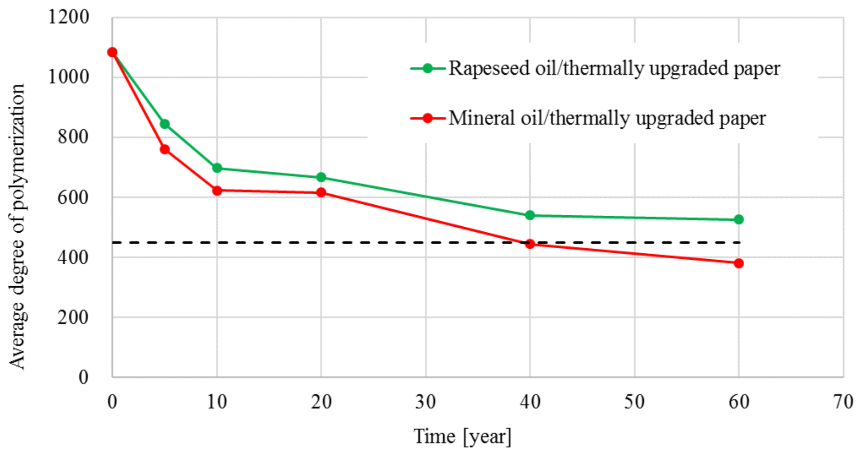

Fig. 6 Average degree of polymerization for insulation paper

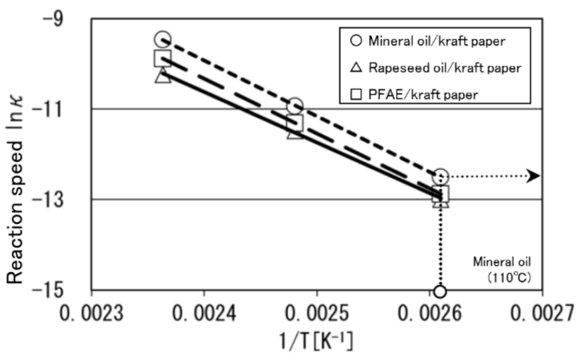

Fig. 7 Arrhenius plot of kraft paper [8]

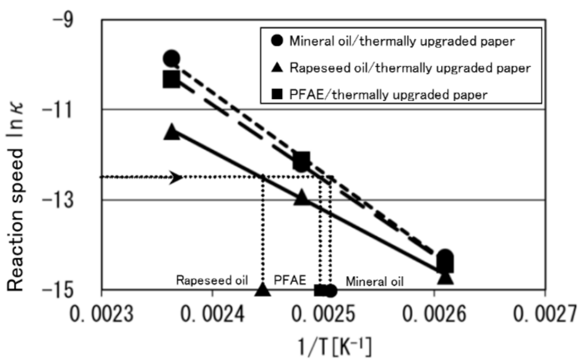

Fig. 8 Arrhenius plot of thermally upgraded paper [8]

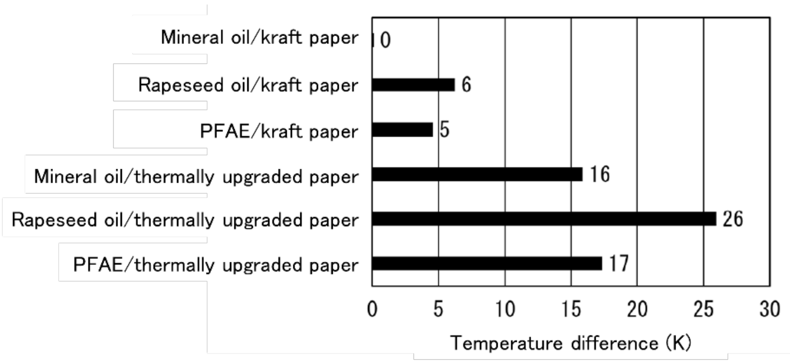

Fig. 9 Temperature differences for oil types based on mineral oil/kraft paper (110°C) using regression [8]

It is known that On Load Tap Changer (OLTC), using natural ester oil, is difficult to operate in low temperature. The mechanical linkage for OLTC is well designed for such condition and its switching performance has been verified even at -15°C. The OLTC chamber is hermetically sealed to prevent deterioration of the insulating oil.

Currently, in Japan, fire extinguishing equipment is required when installing a transformer indoors according to the Fire Service Law. However, if the Law is deregulated, the use of rapeseed oil is expected to simplify the fire extinguishing system in the future. Also if the current regulations in JEAG 5002 are revised to conform to IEC 61936-1:2021, the clearance between adjacent 154kV transformers can be reduced from 7m to at least 4.5m, which will contribute to further downsizing of substations.

5 Conclusions

As a substation that realizes carbon footprint reduction, authors introduced VCBs insulated with synthetic air, a natural origin gas and transformers using rapeseed oil (natural ester oil).

Compared to conventional SF_6 GCB, the VCB can reduce CO_2 emissions by approximately 350 tons per unit. The overall size of the VCB is designed equivalent to that of a SF_6 GCB, applying higher air pressure to increase dielectric strength and VCB enclosure diameter is accordingly minimized not to have impact on its footprint.

By using rapeseed oil in the transformer, CO_2 emissions over the transformer entire life cycle can be reduced to 1/6 of those over the transformer life using mineral oil (CO_2 emissions reduction per rapeseed oil transformer: about 26.5 tons). Also, current carrying design of the transformer achieved a more compact size by setting the temperature rise limit according to IEC 60076-14 instead of JEC-2200-2014. Since the deterioration of the transformers with rapeseed oil is different from that of the transformers with mineral oil, a method for diagnosing their life is a subject for future study.

The carbon footprint reduction equipment reported in this paper can be installed in the substation with the similar design as before. The foundation can be reused for replacement of existing equipment and no additional work is required. In the future, authors will introduce 168kV synthetic air VCB and 84kV synthetic air GIS and further introduce 154kV rapeseed oil transformer and shunt reactor, aiming to create environmentally friendly substations. In addition, by adding digital monitoring technology to the substations, we aim to realize substations with enhanced resilience and solving manpower restrictions.

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