2022 Paris Session

A2-PS2

Development of Transformer using Natural Ester for a Modular Substation

J.PARK*, H.G.JEONG, M.G.KIM, S.E.KIM, J.JUNG, I.C.CHO, J.CHOI, Y.G.KIM
LS ELECTRIC
Rep. of Korea
jyparkb@ls-electric.com

SUMMARY

Recently, substations have been increasingly demanded in mountain and offshore areas to serve the electricity by connecting with renewable energy such as photovoltaic and wind power systems. A modular substation consists of several modular type equipment, which is installed on a trailer or in a container. The purpose of this substation responds to mid or long term electricity demand by connecting to renewable energy facilities, where it is difficult to build new substations. The modular substation is more available solution to provide the electricity than a conventional substation, because the former can reduce the period, cost, and installation area against the latter. Modular type equipment should meet regulations of road transport limitation and should be considered to minimize environmental pollution problem due to installation at sensitive natural area. This paper deals with transformer development with natural ester for a modular substation.

In power transformer applications, a conventional petroleum-based mineral oil has been widely used as a dielectric fluid and a coolant over several decades. However, it may cause environmental and fire safety issues. Thus a natural ester is increasingly recognized as a alternative fluid, because it has a highly biodegradable property and a higher fire point of above 300 degree Celsius. This characteristics are very suitable for installation close to sensitive natural area. In this paper, the specification of transformer for development is 3ph, 60Hz, 154/23kV, 30MVA, HV on OLTC, KNAF using natural ester.

Generally speaking, cooling performance of the natural ester is lower than that of mineral oil, and thus size of transformer using the natural ester is designed slightly bigger than that of mineral oil. Due to fluidity of natural ester, transformer with natural ester has wider cooling duct in winding structure, and the diameters of windings could be bigger. Consequently the total weight of transformer is increased. However, it is necessary to reduce size and weight to keep national rule of weight limitation in transportation. This has been achieved by optimized design using FEM such as electric field and thermo-fluid analysis. Through these design process, the transformer for the modular substation has been suitably designed and tested according to IEC standard.

In addition, this paper presents the ageing behavior of the natural ester and the insulation papers impregnated in the fluid. To investigate the ageing behavior of them, an accelerated degradation test is conducted in temperature-controlled chambers at 130 and 150 degree Celsius for up to 8,000 hours. The resulting expected lifetime of the insulation paper is predicted to about 43 years at the operating temperature of 110 degree Celsius, which is based on the degree of polymerization of 200.

Full arrangement of modular substation of GIS, monitoring system and the transformer is going to be installed on site for pilot test. After a certain period of pilot tests will be performed for the modular substation, the monitoring data of the transformer such as DGA, PD and so on will be acquired.

KEYWORDS

Power transformer, Modular Substation, Natural ester

1. Introduction

Substation is an important facility in power grid to provide a reliable supply of electric power. Unlike the conventional substation, a modular substation(as shown in Figure 1) is a new paradigm substation to respond to power demand. Equipment of substation such as transformer, switchgear, and control panel was modularized and installed on a trailer or in a container. It can be applied to supply power temporary in mid/short term when a substation facility is faults and to connect renewable energy. Recently, substations have been increasingly demanded in mountain and offshore areas to serve the electricity by connecting with renewable energy such as photovoltaic and wind power systems. The modular substation is applied for special places such as islands, jungles, and seas. The purpose of the modular substation responds to mid or long term electricity demand by connecting to renewable energy facilities, where it is difficult to build new substations rather than replacing conventional substations.

The modular substation has several advantages. First of all, it can be reduced construction period, cost and site area of substation. The other is to install and move freely than conventional substation and each equipment is connected by plug and play for convenience of installation. Modular type equipment should meet regulations of road transport limitation and should be considered to compact design due to limitation of site area. And, it should be considered to minimize environmental pollution problem due to installation at sensitive natural area. This paper is about transformer development with natural ester for a modular substation.

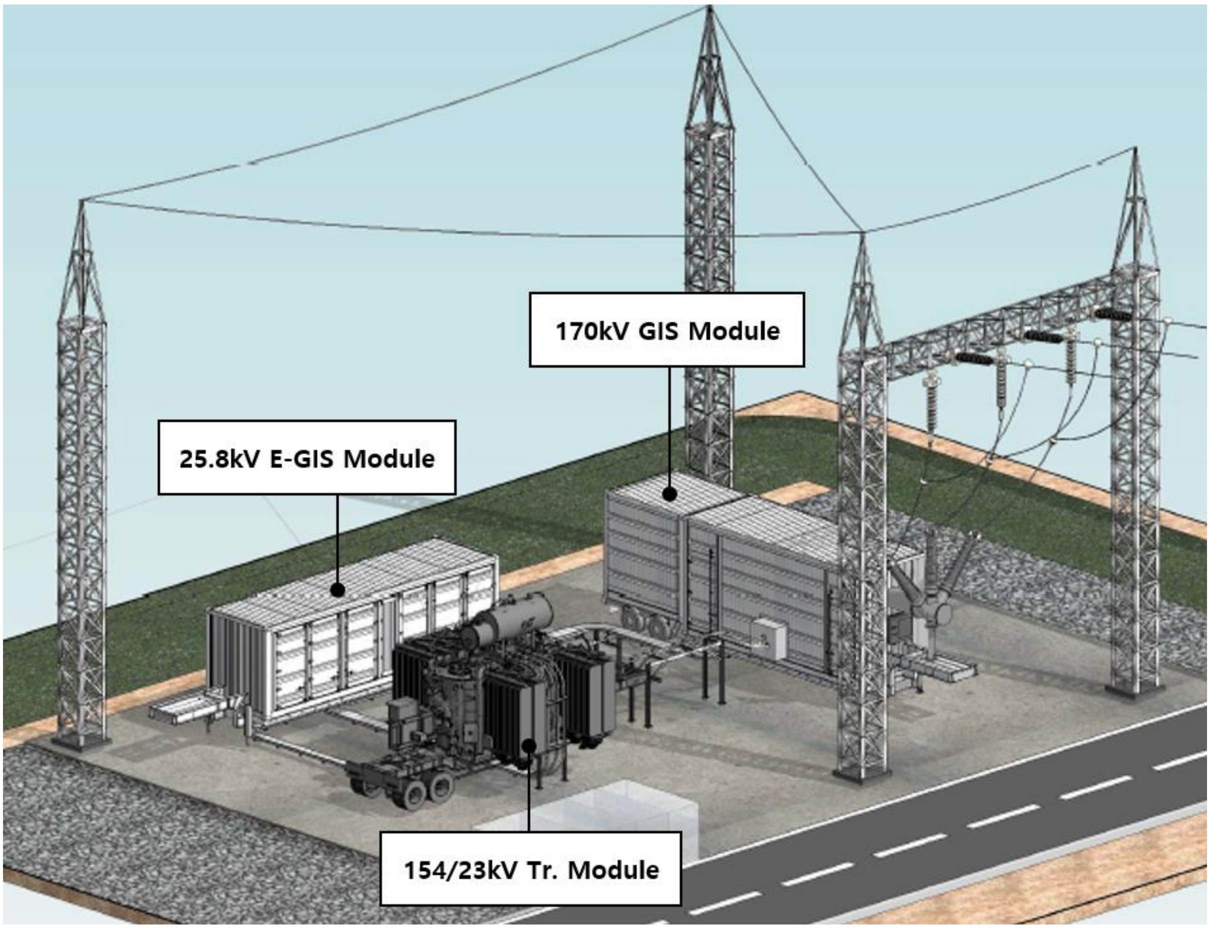


Figure 1 – Layout of modular substation

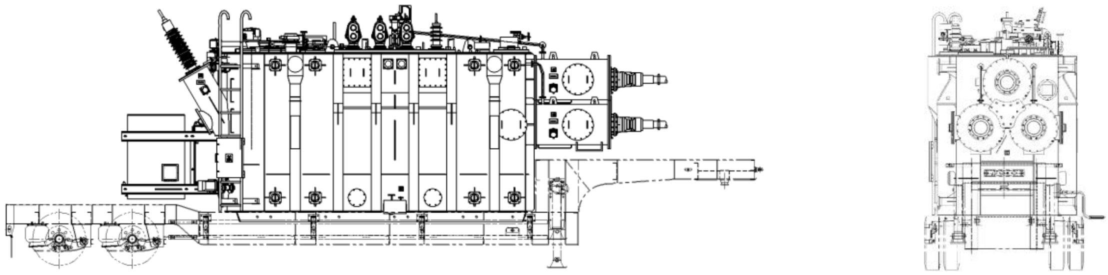
2. Transformer for modular substation

2.1. Specifications

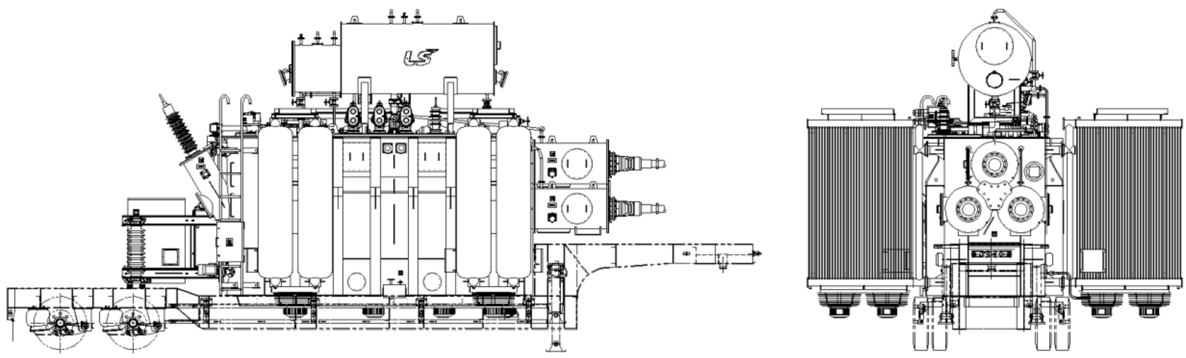
The specifications of the transformer for modular substation developed are shown in Table 1. There are no standards for transformer for modular substation, the specifications of the developed transformer were decided referring to the standards of the existing KEPCO 154kV transformer. To minimize environmental pollution problem, natural ester was applied to transformer for modular substation. Due to install and move freely, the design of transformer for modular substation needs to consider limitation of road transportation in Rep. of Korea. As the rate capacity increases, the weight of transformer increases. So, a feasible rate capacity of the transformer was decided to 30MVA. Also, to consider the limitation of road transportation, some parts are transported separately such as oil, radiators, fans and conservator. And to reduce maintenance point, a cooling method without a pump was selected. Outline of transformer for modular substation is shown in Figure 2.

Table 1 – Development specifications of transformer

<table>
<tr><th colspan="3">Description</th><th>Spec.</th></tr>
<tr><td colspan="3">Phase</td><td>3</td></tr>
<tr><td colspan="3">Frequency</td><td>60 Hz</td></tr>
<tr><td colspan="3">Rated voltage (HV/XV/TV)</td><td>154 / 23 / 6.6 kV</td></tr>
<tr><td colspan="3">Ratio</td><td>154 kV ± 8 x 1.25%</td></tr>
<tr><td colspan="3">Rated capacity</td><td>30 MVA</td></tr>
<tr><td colspan="3">Cooling type</td><td>KNAF</td></tr>
<tr><td colspan="3">Insulation liquid</td><td>FR3</td></tr>
<tr><td colspan="3">Impedance (HV – XV)</td><td>12 ± 7.5%</td></tr>
<tr><td colspan="3">Peak Efficiency Index</td><td>99.671%</td></tr>
<tr><td rowspan="5">Dielectric test level</td><td rowspan="3">HV</td><td>FW</td><td>650 kV</td></tr>
<tr><td>CW</td><td>715 kV</td></tr>
<tr><td>AC</td><td>275 kV</td></tr>
<tr><td rowspan="2">HVN</td><td>FW</td><td>325 kV</td></tr>
<tr><td>AC</td><td>140 kV</td></tr>
<tr><td colspan="3">Max. ambient temperature</td><td>40 degree Celsius</td></tr>
<tr><td rowspan="3">Temperature Rising</td><td colspan="2">Average winding</td><td>65 K</td></tr>
<tr><td colspan="2">Hot – spot</td><td>78 K</td></tr>
<tr><td colspan="2">Top oil</td><td>60 K</td></tr>
</table>



(a) Transportation

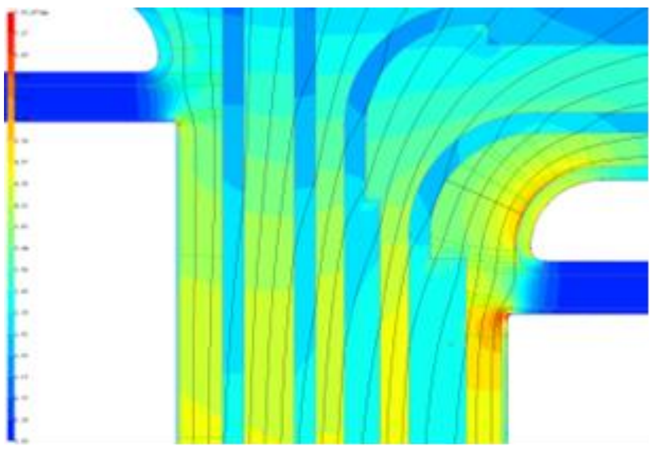


(b) Installation

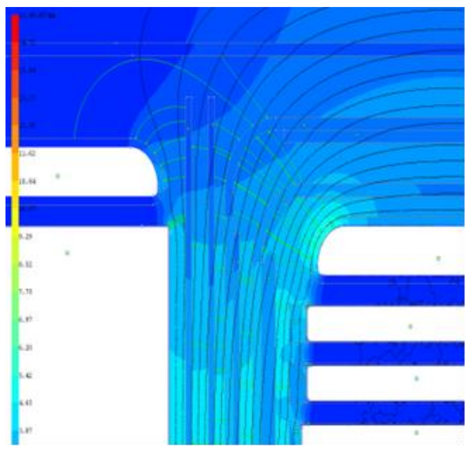
Figure 2 – Transformer on trailer

2.2. Insulation design

Insulation design is the most important design step in a transformer. The most important of various types of transformer tests is the insulation level test. Therefore, insulation performance must be considered from the early steps of transformer design. However, while mineral oil transformer design is enough experienced, natural ester transformer design is a few experienced. Therefore, in this paper, insulation design and analysis of most of the insulating structures, including parts considered week point for example especially the main end-insulation.Thus, it could be manufactured to have an insulating distance similar to that of the mineral oil transformer.



(a) Mineral oil condition



(b) Natural ester condition

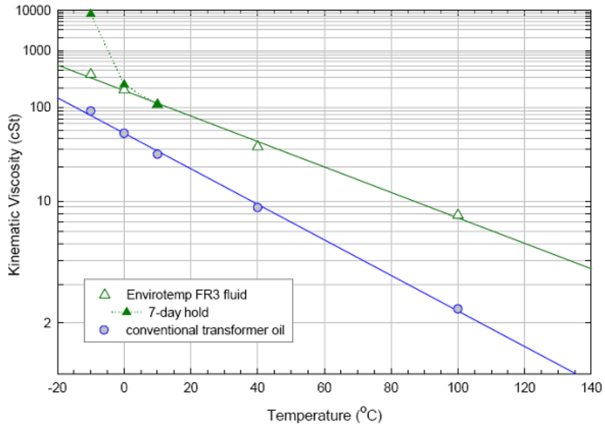
Figure 3 – Results of electric field anaylsis with different oils

2.3. Cooling design

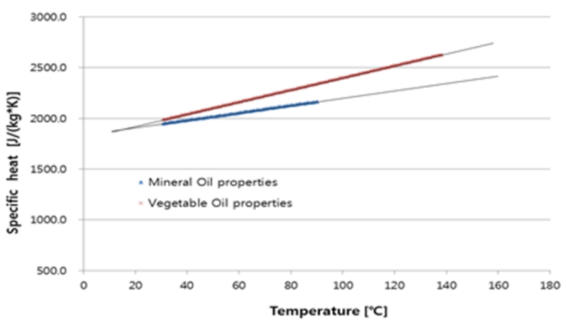
There are two aspects to decide cooling performance of transformer. First aspect is the structure such as cooling ducts in winding, radiator size, pump capacity and performance of cooling fan. And second aspect is material properties like kinetic viscosity, heat conductivity and specific heat. In case of natural ester filled transformer, though structure is similar with mineral oil one, cooling performance is mostly determined to consider its material characteristics[1].

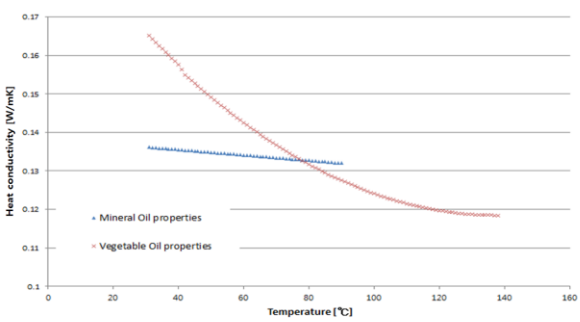
2.3.1. Compared with material characteristic of mineral oil and natural ester

First of all, to apply natural ester in transformer, viscosity is one of the most important characteristic. If the viscosity is lower and lower, insulation oil at a high temperature is quickly moved to radiator and heat is radiated. Therefore, insulation oil in transformer is needed lower viscosity characteristic. But, natural ester has higher viscosity than mineral oil. It leads to make poor cooling performance and raise temperature at insulation material such as pressboard and insulation paper. As a result, it affects lifetime of transformer. Kinetic viscosity characteristics of mineral oil and natural ester are shown in Figure 4(a). Second characteristic is specific heat. When specific heat characteristic is increased, quantity of heat is more needed to raise temperature. As a result, heat of winding move to insulation oil, effect of temperature rising is quite different by what insulation oil used. Specific heat characteristics of mineral oil and natural ester according to temperature variation are shown in Figure 4(b). Third is heat conductivity. If heat conductivity become higher and higher, heat of winding is transmitted quickly to insulation oil and heat of radiator is radiated quickly. As a result, it leads to make a good cooling performance. Heat conductivity characteristics of mineral oil and natural ester according to temperature variation are shown in Figure 4(c).



(a) Kinetic viscosity





(b) Specific heat (c) Heat conductivity

Figure 4 – Material characteristics of mineral oil and natural ester

2.3.2. CFD Analysis

Due to characteristic of higher viscosity, cooling system's performance using natural ester is expected to be lower. On the contrary, natural ester has higher specific heat and heat conductivity and this may compensate insufficient cooling performance. B.H.Bae et al.[1] found that the temperature of natural ester is higher about 3 degree Celsius than mineral oil. Base on the previous test results, inlet temperature was applied as boundary condition. Analysis model and boundary conditions of cooling performance are shown in Figure 5. Average winding temperature of the developed transformer is raised to 4~5 degree Celsius, hot-spot temperature is raised to 6~7 degree Celsius by CFD analysis. Results of CFD analysis in windings are shown in Table 2.

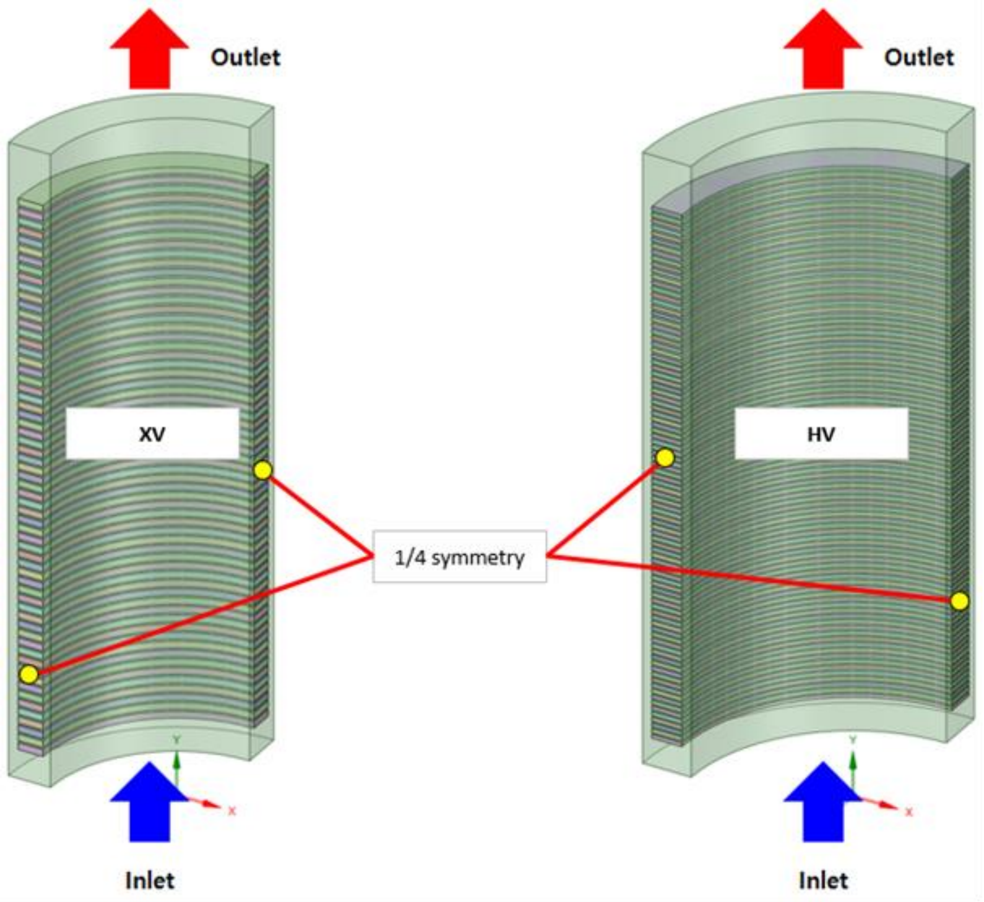


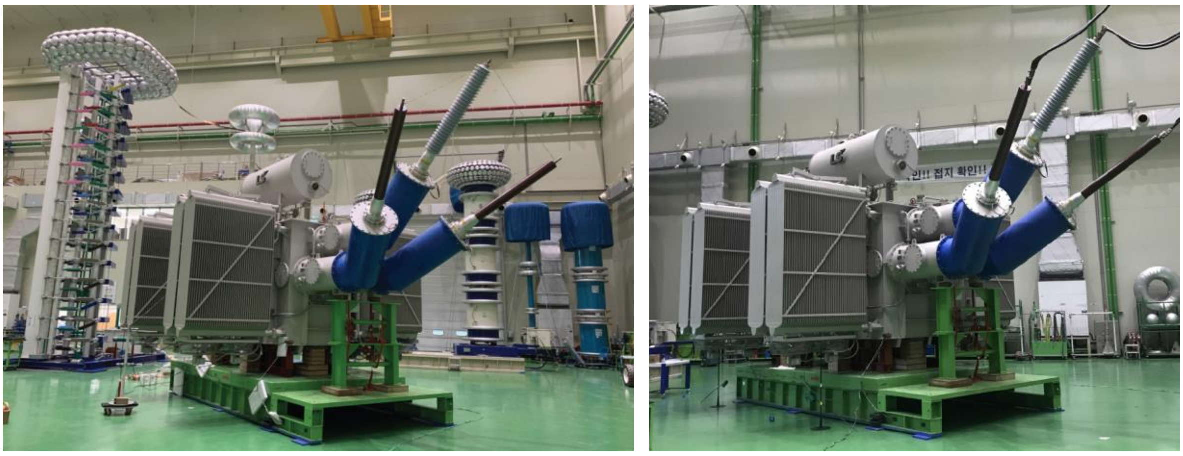
Figure 5 – Analysis model and boundary conditions for CFD anslysis

Table 2 – Results of CFD analysis

	Inlet oil (℃)	HV (K)		XV (K)	
		Avg.	Hot-spot	Avg.	Hot-spot
Mineral oil	66.9	52.6	55.8	52.9	57.9
Natural ester	69.9	57.1	62.2	57.8	64.8
Temp. gap	+ 3	+4.5	+6.4	+4.9	+6.9

2.4. Type test and interworking test

The type tests were carried out for the developed transformer to verify its performance. The developed transformer has passed all the tests. It is confirmed that the developed transformer has sufficient performances. The type test of the developed transformer is shown in Figure 6.



(a) Dielectric test (b) Temperature rising test

Figure 6 – Type test of transformer for modular substation

The modular substation consist of modular type equipment such as the transformer, 170kV GIS and 25.8kV E-GIS. Due to connect by many power and control cable of plug and play type, interoperation test was needed before move to install. The interworking test with the other modular type equipment is shown in Figure 7.

Figure 7 – Interoperation test of modular type equipment

3. Accelerated degradation test

Natural esters have been increasingly preferred as dielectric fluids in power transformers due to environmental and fire safety issues over conventional mineral oils. This section presents ageing behaviours of cellulose-based insulation papers impregnated in dielectric natural ester. In the experiment, the degradation of the insulation paper impregnated in natural ester is investigated at each sampling interval in terms of the degree of polymerization. The thermal behaviours under natural ester are also compared with under the conventional mineral oil.

3.1 Experimental setup

In the experimental setup, sealed steel cylinders filled with dry nitrogen, containing copper bar, core, pressboard, insulation paper and dielectric oil, are aged in temperature-controlled chambers, in order to investigate ageing behaviours of insulation papers impregnated in natural ester and compare with those in the conventional mineral oil.

The two different sample sets are prepared to compare the thermal behaviours of the paper impregnated in different insulating oils. First, steel cylinders are prepared, in which the thermally upgraded insulation paper, the non-thermally upgraded pressboard, copper bar, core, and insulation oils are maintained. Before placing into the cylinders, the thermally upgraded insulation paper and the non-thermally upgraded pressboard are dried under vacuum in order to reach the acceptable moisture content less than 0.5% moisture content, which are close to new transformer conditions. After completing the moisture condition process, the dried paper and pressboard are accommodated with cooper bar and core. Then these are impregnated in the conventional mineral oil for one set, and in natural ester for the other set. The commercially available Envirotemp FR3 fluid is used as the natural ester in this experiment. Second, both the two sets of steel cylinders are tightly sealed and headspaces of the cylinders are filled with dry nitrogen blanket in order to eliminate the oxidation effect of the insulation oils. Third, the cylinder sets are then placed inside two temperature-controlled chambers for ageing up to 8,000 hours. In detail, the cylinder set filled with mineral oil are aged at 130 degree Celsius for up to 3,500 hours. While, the cylinder set filled with FR3 are aged at both 130 degree Celsius and 150 degree Celsius for up to 8,000 hours. These aged sealed cylinders are sampled at each appropriate intervals to analyse the degradation behaviours of the insulation papers and the insulation oils.

3.2 Test results

3.2.1 Degradation behaviours of the insulation paper

The degradation behaviours of the insulation paper impregnated in the FR3 fluid are compared with those of impregnated in conventional mineral oils. The decreases in the degree of polymerization (DP) values of the aged insulation papers impregnated in both mineral oil and the FR3 fluid, aged at the temperature of 130 degree Celsius, are compared in Figure 8. As shown in Figure 8, the DP value of the insulation paper in mineral oil has rapidly reached to 58 % of the initial value at the ageing time of 3,500 hours. While, the DP value in the FR3 fluid shows a small decrease, maintaining 87 % level of the initial value at the same ageing period of in mineral oil, and further shows only 27 % decrease from the initial value even at 8,000 hours of the ageing time. It means that degradation of the insulation paper in natural ester proceeds slowly, compared to in the conventional mineral oil.

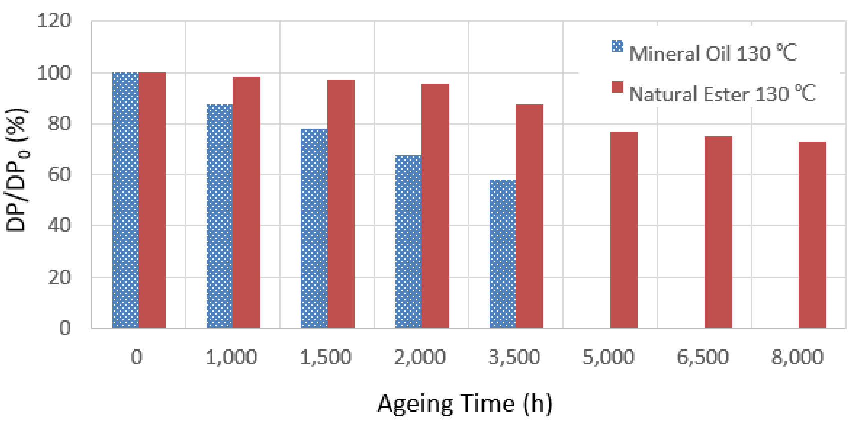


Figure 8 – DP values of the paper impregnated in mineral oil and natural ester

The AC breakdown voltage of dielectric insulation oil is one of key parameters to judge the dielectric performance. As the insulation oils are aged during the tests, the AC breakdown voltages with the concentration of the water contents in both mineral oil and FR3 fluid are compared in Figure 9. As shown in Figure 9, the breakdown voltage of the mineral oil has been drastically decreased to 26 kV at 2.5 mm gap, in which the water content is only 65 ppm. While, the breakdown voltage of the FR3 fluid, the natural ester, has been maintained above 60 kV at 2.5 mm gap, and even in which the water content is increased up to 330 ppm. This means that the breakdown voltage of the natural ester is more tolerable to the moisture than that of the conventional mineral oil.

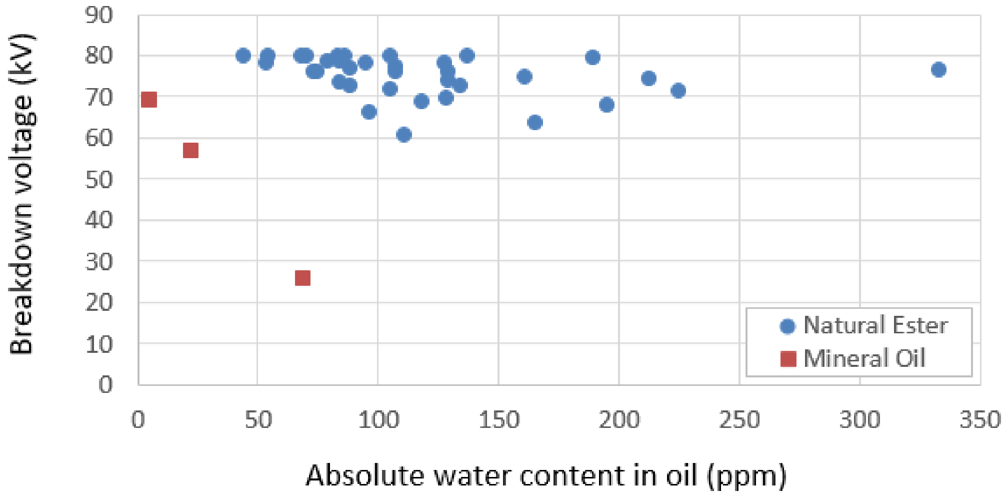


Figure 9 – AC breakdown voltages vs. absolute water contents in oils

The changes of colours in the FR3 fluid are shown in Figure 10, in terms of the DP values of the insulation paper, as the aging has been proceeded. As shown in Figure 10 the colour of the FR3 fluid has been changed from the light green, the new condition, to the dark black, the aged condition after 8,000 hours, as the DP values of the insulation paper have been decreased with ageing. It means that the colour of the FR3 fluid are changed with dark as the insulation paper are getting degraded.

In summary, it is mentioned from the above test results that the insulation paper impregnated in FR3, the natural ester shows a slower degradation than that in the conventional mineral oil.

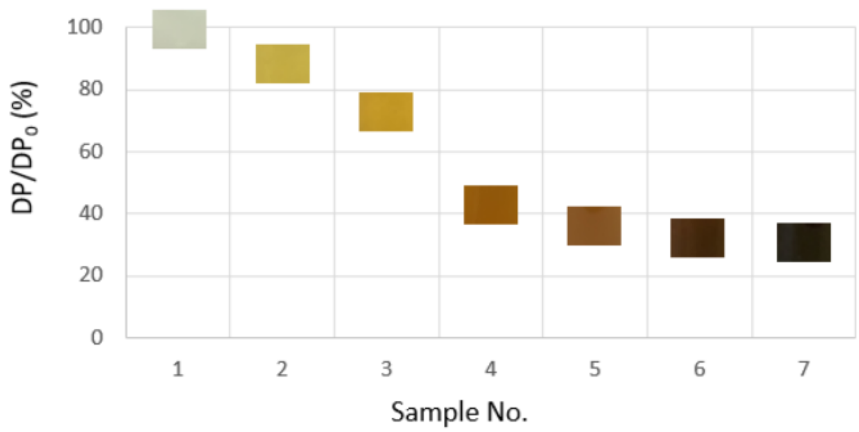


Figure 10 – Colour changes of the natural ester, FR3 with the degradation of the TUK

3.2.2 Lifetime prediction

Emsley and Stevens [2] have suggested that the rate of reaction of the cellulose-based insulation paper is proportional to the number of unbroken polymer chains, i.e., the degree of polymerization of the insulation paper. By the characterization of the temperature dependence of the reaction rate using the Arrhenius relationship, the expected lifetime of the insulation paper can be estimated from the slopes of the reaction rate versus the ageing time. Figure 11 shows the plots of the reaction rate in terms of the degree of polymerization of the insulation paper with the ageing time against the different ageing temperatures of 130 degree Celsius and 150 degree Celsius. From the slopes of the plots in Figure 11, the activation energy of the insulation paper impregnated in the FR3 fluid are analysed. In this case, the expected lifetime of the insulation paper is predicted to about 43 years at the operating temperature of 110 degree Celsius, in which the degree of polymerization of 200 is used as the end of life criterion.

In summary, it is demonstrated through the experiment that the expected lifetime of the insulation paper in the natural ester is much longer than that of in the conventional mineral oil.

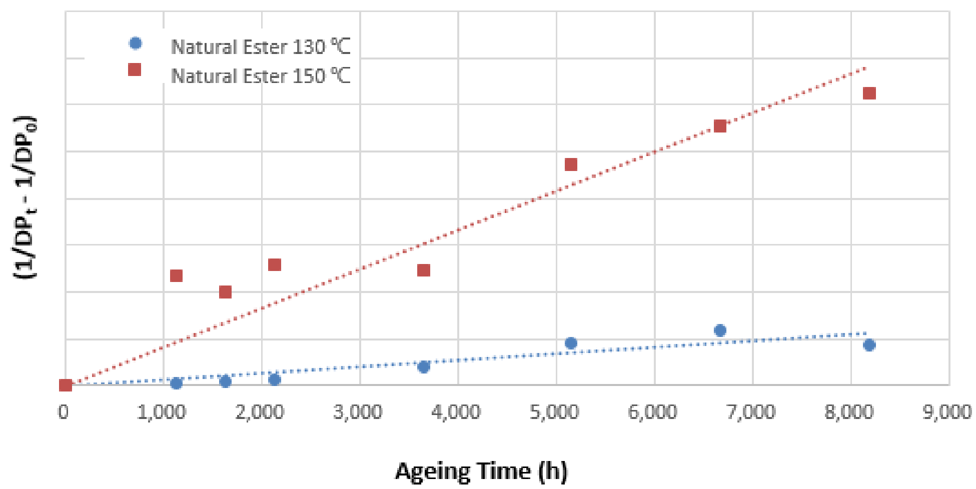


Figure 11 – The reaction rate of the insulation paper with ageing time

4. Conclusion

1) A 154kV transformer using natural ester for modular substation has been developed. The type tests has been carried out. The test results showed that the developed transformer has sufficient performances.
2) The resulting expected lifetime of the insulation paper in natural ester is predicted to about 43 years at the operating temperature of 110 degree Celsius, which is based on the degree of polymerization of 200.
3) As shown in Figure 12, at the end of 2021, full arrangement of modular substation of 170kV GIS, 25.8kV E-GIS, monitoring system and the transformer is installed at on site for pilot test. After a certain period of pilot tests will be performed for the modular substation, the monitoring data of the transformer such as DGA, PD and so on will be acquired.

Figure 12 – Installation of modular type equipment for pilot test

BIBLIOGRAPHY

[1] B.H.Bae, S.E.Kim, J.Choi, S.W.Park, Y.G.Kim "Design of 154kV power transformer using natural ester oil", CIGRE, 2016, A2-305

[2] A. M. Emsley and G. C. Stevens, "Kinetics and Mechanisms of the Low-Temperature Degradation of Cellulose", J. Cellulose, 1994, 1, 26-56