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Application of vegetable oil-based insulating fluids to hermetically sealed power transformers

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SUMMARY

This paper describes the investigation of chemical, electrical and cooling properties of various natural esters. Furthermore the impacts of these properties on design and operation of hermetically sealed power transformers with on-load tap changer are depicted.
Three natural and one synthetic ester were compared to inhibited mineral oil under new conditions and after ageing. The *water solubility* in natural esters is around 15 times higher than that in mineral oil. An equilibrium chart for the moisture distribution between natural ester and Kraft paper is shown in this contribution. The *ageing stability* for the esters and mineral oil was investigated by a heat-accelerated test paying special regard to the oxidation stability. As oxidation processes dramatically increase the viscosity for the natural esters in open systems, an application in open breathing transformers should be avoided. Concerning all other investigated parameters the esters showed similar or better properties than mineral oil.
The investigation of *breakdown strength* for homogeneous field indicates that at moisture saturations typical for transformers the esters perform better than mineral oil. Furthermore moisture has the same influence on breakdown voltage for all fluids. Extensive breakdown tests have been performed on on-load tap-changers of various designs. While the long gaps behaved almost the same as in mineral oil, restrictions in dielectric strength for natural esters appeared on special tap-changer electrode configurations.
In order to guarantee an accurate *thermal design*, different material parameters, e.g. viscosity, heat capacity, thermal conductivity and specific gravity, were determined. Because of the different properties of vegetable-based oils the temperature distribution in windings was calculated by simulating the oil flow by means of a finite element program based on CFD-Codes (Computational Fluid Dynamics).
To ensure and maintain optimum performance of natural esters, exposure to oxygen and moisture must be minimized. Thus *hermetic sealing* against ambient air is the best way to benefit from the characteristics investigated before. The paper presents the special considerations for design, impregnation and operation of a conventionally sealed 90 MVA/132 kV transformer and a hermetically sealed 40 MVA/110 kV transformer with expandable radiators using vegetable-based oil as insulating and cooling medium. Compared with standard transformers the hermetic power transformer with a vacuum type tap- changer has not only the advantage of less ageing, it also requires less maintenance during the total lifetime. The conditions and limitations for trouble-free service are defined.

KEYWORDS

Power Transformer - Natural Ester – Water Saturation –Ageing Stability – Dielectric Strength - Thermal Design - OLTC – Hermetical Sealing

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1 INTRODUCTION

The demand for environmentally friendly dielectric fluids in distribution and power transformers is rising as the environmental impact of conventional fluids becomes increasingly more apparent. Vegetable-based insulating oils are now commercially available as substitutes for mineral-based oils in transformer applications. Some advantages offered by these oils, which are chemically classified as Natural Esters, are the faster biodegradability, no water hazard, higher flash/fire points and low thermal expansion coefficient. Thus the application of these liquids in power transformers promises strong benefits, compared to conventional mineral oil. Nevertheless the different chemical and physical characteristics require special considerations. Especially the degradation of the fluid in the presence of oxygen, different cooling and dielectric properties have to be taken into account for a reliable design and operation of power transformers.

2 WATER SOLUBILITY AND AGEING STABILITY

Three natural and one synthetic ester were compared to inhibited mineral oil under new conditions and after ageing regarding various parameters: water solubility, breakdown voltage, ageing stability, neutralization number, dissipation factor, conductivity, viscosity, pour point, colour, density and flashpoint. Investigations were done by means of natural ester (Envirotemp FR3 fluid, Midel eN and high-oleic sun flower oil), synthetic ester (Midel 7131) and mineral oil (Nynas Nytro 3000 X) [1 - 4].
The *water solubility* in all three natural esters is similar and around 15 times higher than that in mineral oil (Fig. 1, left); the synthetic ester dissolves around 40 times more water. Fig. 1 (middle) displays a moisture equilibrium chart for natural ester and Kraft paper. Based on equilibrium charts the moisture distribution between the solid and the fluid insulation and the effect of an oil exchange by an ester can be calculated. For a transformer having 7 t of cellulose at 3 % average moisture content and 70 t of aged mineral oil at 40°C the oil contains only 3 kg water, whereas the cellulose has 210 kg. After oil exchange with a natural ester the fluid takes up 14 kg of water, slightly decreasing the water content in the cellulose to 199 kg. Thus an oil exchange by a natural ester cannot dry a transformer, but would increase the efficiency of transformer drying by continuous oil circulation.

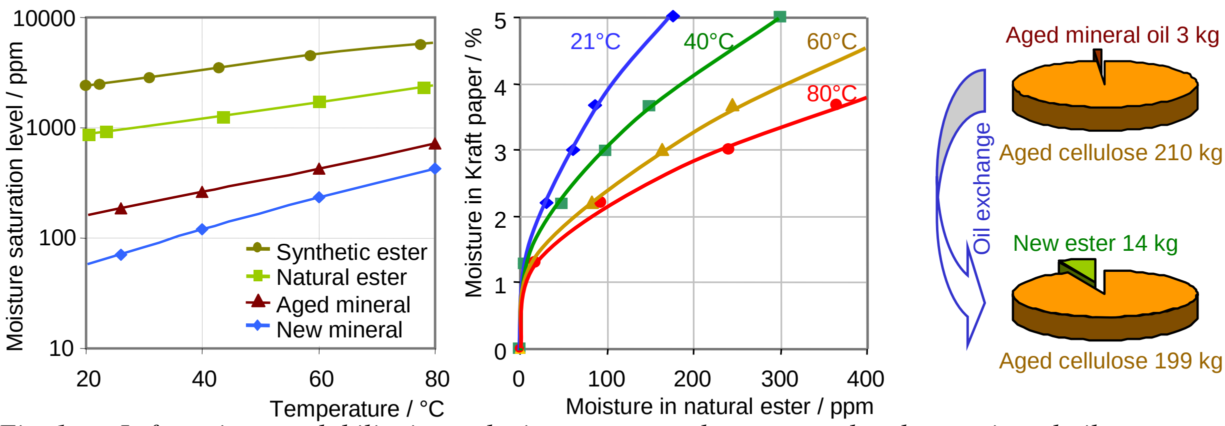

Fig. 1: Left: moisture solubility in synthetic ester, natural esters, aged and new mineral oil, middle: moisture equilibrium chart for natural ester and Kraft insulation paper right: moisture distribution between cellulose and oil for aged mineral oil and after oil exchange for new natural ester at 40°C

The *ageing stability* for the esters and mineral oil was investigated by a heat-accelerated test at 130°C lasting for 1440 h following EN 14112 and EN 61112. A comparison of ageing in a closed vessel to that in an open one determined the oxidation stability. All vessels contained materials typical for transformers such as Kraft paper and pressboard (mass ratio 1:10 to oil), copper, aluminium, tin and iron.
Fig. 2 (left) depicts the kinematic viscosity of all fluids under original new and aged conditions in open and closed systems. As the viscosity dramatically increases for the natural esters (NE) in open systems, this test impressively illustrates the impact of oxygen on the ageing performance. Oxidation splits the ester molecules into smaller fractions. The remaining molecules polymerize increasing the viscosity. Conclusively an application in open breathing transformers should be avoided.

Fig. 2 (right) reveals that natural esters behave more paper-friendly during ageing. The degree of polymerisation of paper samples aged in natural ester is clearly higher than that in the synthetic ester and in mineral oil.

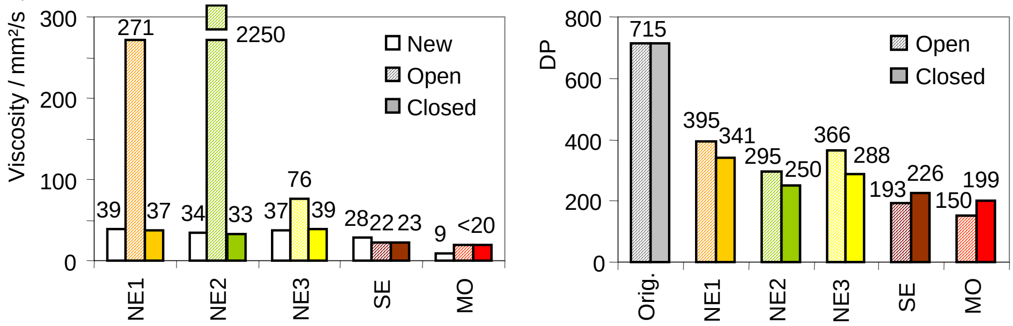

Fig. 2: Ageing experiments with open and closed systems for the natural esters (NE), synthetic ester (SE) and mineral oil (MO); left: kinematic viscosity at 40°C; right: degree of polymerisation of Kraft paper samples aged in the fluids

3 DIELECTRIC PROPERTIES

3.1 Breakdown Strength under Homogeneous Field Condition

The breakdown strength of the esters and mineral oil as mentioned in the ageing test of section 2 was investigated under homogenous field conditions at different relative moisture saturations. The tests were carried out according to IEC156/95 Fig.II (VDE0370/Teil5/96 and ASTM D1816), i.e. spherical electrodes with 25 mm radius and 2.5 mm electrode gap. Fig 3 (left) indicates that at moisture saturations typical for transformers (< 20 %) the esters perform better than mineral oil. Furthermore moisture has the same influence on breakdown voltage for all fluids. Fig 3 (right) shows the breakdown voltages at 20 % moisture saturation before and after ageing. Only for mineral oil the breakdown voltage decreases due to ageing.

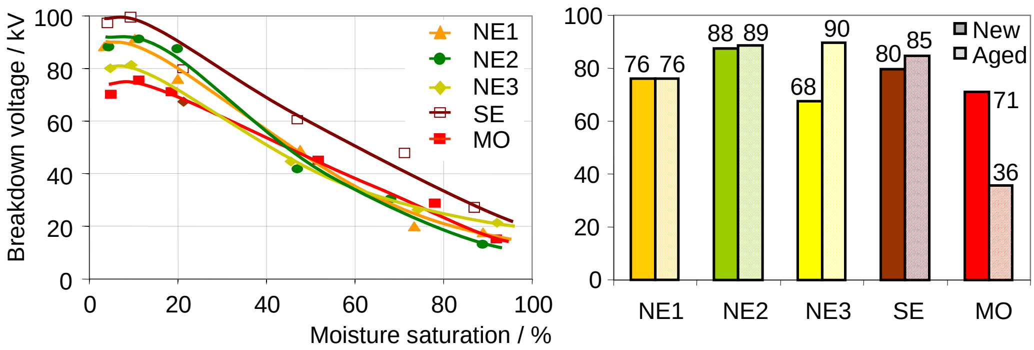

Fig 3: Left: breakdown voltage of esters and mineral oil depending on moisture saturation Right: breakdown voltage before and after ageing at 20 % moisture saturation

3.2 Breakdown Strength under Inhomogeneous Field Condition

For testing under non-uniform electrical field a test cell with a volume of 1.5 l and point-plate electrodes was used. The diameter of the plate electrode was 35 mm. The distance between electrodes was 30 mm and there was no oil stirring during the test.

Table I – Oil breakdown testing under non-uniform electrical field

Power Source	Gap [mm]	Oil Type	RH [%]	U_m [kV]	s [%]	$U_{1\%}$ [kV]
AC 50Hz (non-uniform field)	30	NN3000X	11	56.0	9	40.1
		NE 1	12	53.0	7	41.5
		NE 2	10	55.6	8	42.0
LI 1.2/50µs (non-uniform field)	40	NN3000X	9	91.6	4	77.7
		NE 1	7	100.3	3	90.2
		NE 2	7	115.2	6	99.4

The lighting impulse tests were done with 1.2/50 µs impulses of positive polarity. After drying, filtering and before breakdown tests relative humidity (RH) of the oil was measured. The distance between the electrodes was 40 mm. Measurements were carried out according to the VDE 0432-1 (IEC 60060-1) class 2. This procedure involves up-and-down tests method. After breakdown a 5 minutes pause followed before the next, one step lower impulse was applied. The voltage steps were 3 kV. For each of the oils after 25 breakdowns mean breakdown voltages (U_m) and standard deviations (s) were calculated (Table I). Also the values for 1 % breakdown probability ($U_{1\%}$) according to two-parameter Weibull cumulative distribution function were calculated. Both tests show that for gap distances up to 40 mm natural esters have a similar insulation strength compared to mineral oil.

3.3 Tap-Changer Electrode Configurations

On-load tap-changers (OLTCs) show many different electrode configurations, due to different functional requirements. The insulating distances which can be found there may be homogeneous or highly inhomogeneous. In case electrical insulation is the only function, the geometry can be optimized for smooth field distribution. For the OLTC type shown in Fig. 4, the shielding rings of the “phase-to-phase” and “phase-to-ground” distances (see arrows) were consequently designed to minimize field strength. For other insulating gaps like “tap-to-tap” or “across regulating range”, the geometric shape is the result of a compromise between mechanical function, mechanical endurance, number of taps, required load current and electrical insulation. This is clearly visible in Fig. 5, showing a tap selector with its many different insulating gaps. It can be seen, that the different potentials of all conducting parts of this construction cause many different field distributions, which are necessarily inhomogeneous. Nevertheless, the dielectric strength has been proven by numerous calculations and tests to be sufficient in mineral oil, confirming the nominal withstand voltages of the standard coordination of insulation.

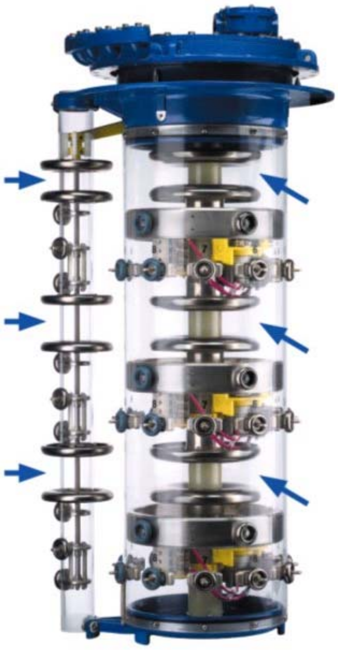

Fig. 4: Vacuum type OLTC with optimized shielding rings to ensure homogeneous field distribution

Fig. 5: Tap selector showing numerous inhomogeneous insulating gaps

The relevant design tests are manifested in the international standards like IEC 60214-1. Beyond that, additional tests of the dielectric strength are performed to ensure reliable statistics. A test procedure has been developed, which is commonly applicable for all dielectric tests. This method has been applied to different tap-changer types in combination with natural ester. Long homogenous shapes like the “phase-to-phase” and “phase-to-ground” distances (Fig. 4) showed a dielectric strength similar to mineral oil. The nominal withstand voltages could be fully confirmed. In contrast, inhomogeneous configurations (Fig. 5) performed different, showing significantly reduced withstand voltages. For AC, 74-77 % of the nominal values (valid for mineral oil) could be achieved. For impulse voltage, only 63-65 % of the nominal values were confirmed as statistically safe. This behaviour has been proven as typical for inhomogeneous gaps with a clearance of 5-10 cm, where AC test voltages up to 190 kV and impulse voltages up to 650 kV are applied.

4 THERMAL PROPERTIES

In Tab.II the relevant properties for thermal considerations of a typical mineral oil and vegetable based oil FR3 are compared to each other [1]. The decrease of density at increasing temperature is also approximately the same and therefore the available pressure difference for driving the natural oil convection is also equal. The heat conductivity of FR3 is about 40 % higher than for mineral oil, which mainly leads to a better heat transfer from insulation surfaces to the oil and therefore to a lower temperature difference between surface and surrounding oil. Also the radiators could be designed smaller because of the improved inner heat transfer. The main drawback of the vegetable oil seems to be its more than five times higher viscosity, compared to the mineral oil, since the hydraulic resistance of the winding at low flowrates, according to ON-cooling, is roughly proportional to the viscosity. Since natural cooled transformers have no pump for the oil, the natural driving force has to be increased by lifting up the radiators or the hydraulic resistance has to be decreased by increasing the dimensions of the oil channels in the windings. An advantage of the higher viscosity could be the lower Reynolds-Number at a given flowrate. Especially at higher flowrates, separation at branches occur less and the flow distributes more equal on the channels between the discs.

Table II: Properties of mineral oil versus properties of vegetable oil

Temperature in °C	Heat conductivity in W/(m K)		Specific heat capacity in J/(kg K)		Density in kg/m^3		Dynamic viscosity in mPa s	
	Shell Diala DX	Enviro. FR3	Shell Diala DX	Enviro. FR3	Shell Diala DX	Enviro. FR3	Shell Diala DX	Enviro. FR3
20	0.124	0.167	2020	1850	874	923	14.9	86.3
60	0.122	Not avail.	2195	2120	848	898	3.8	22.3
100	0.199	Not avail.	2370	2390	822	872	1.7	8.6

To make a representative comparison for practical cases, a typical winding design of a disc-type winding was investigated. After each pass of eight discs a washer is arranged to break the vertical oil channel at alternating sides. This leads to an oil flow in a zigzag manner. The simulation was done by impressing a defined oil velocity at the inlet, while in the conductors a known loss density was impressed. The coupled equations for flow and heat transfer were solved simultanously. Since the effect of the spacers can be neglected, a 2D model with rotational symmetry is sufficient. The arrangement was modelled with the commercial software "CFX" with about ¼ mio. elements.

Fig. 6 shows the computed temperature distribution in the winding. Because of the effects of the adiabatic boundary in the upper and lower axial end, only the middle part is representative for a real case and therefore only this part is displayed. The temperature distributions look quiet similar for both types of oil, while the hot spot temperature for the case with mineral oil is about 1°C higher than in the case with vegetable oil. This seems to be the effect of the above mentioned higher heat conductivity of vegetable oil. It is noted that the impressed flow rate in this simulation does not consider the balance between pressure drop with hydraulic resistances and available pressure for driving the flow. For these considerations, the whole hydraulic circuit of the transformer has to be analysed. As mentioned above, for the same flow rate with vegetable oil, it is necessary to reduce the hydraulic resistance of the circuit or to increase the driving pressure for the oil. For layer windings the use of natural esters can be beneficial due to the lower hydraulic resistance.

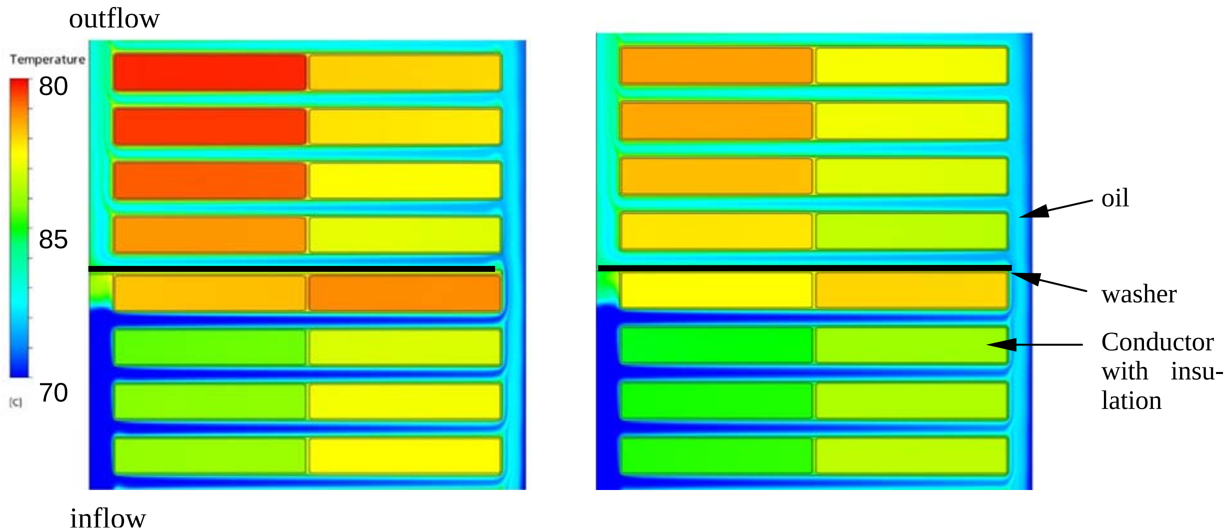

Fig. 6: Temperature distribution in the winding cooled with mineral oil (left) and with natural ester (right) at same flowrate and inlet temperature

Since the higher viscosity of vegetable oil is adverse for the cooling while the higher heat conductivity is advantageous, neither a quantitative nor a qualitative statement about the hot-spot temperature can be made for generality. For such a statement, each specific case has to be investigated separately i.e. the complete system especially of the windings and the radiators has to be investigated as a whole.

5 ON-LOAD TAP-CHANGERS FILLED WITH NATURAL ESTER

5.1 Arc-breaking-in-oil tap-changers vs. vacuum switching technology

The arc-breaking behaviour of contacts is a complex process which is influenced by the viscosity and the thermal properties of the liquid, as well as the contact speed, the contact material and the shape of the contact system. To ensure a reliable function of the tap-changer, it is essential that the switching arcs are extinguished within fixed time limits. It has been found that the arcing time in natural ester is significantly longer than in mineral oil. Prolonged arcing times lead to excessive contact wear and increased oil deterioration, so that maintenance intervals have to be shortened. Furthermore, the required timing sequence of the OLTC design may be violated. Consequently, the use of alternative liquids, with natural ester among them, is not recommended for arc-breaking-in-oil tap-changers.

A new switching technology uses vacuum interrupters, which fully encapsulate the switching arc. OLTCs using this vacuum technology are principally suitable to be operated in alternative liquids, showing the same switching performance like in mineral oil. Based on a wide variety of tests which were performed, approvals for natural ester and other alternative liquids could be prepared for these OLTC types. Due to the fact, that almost no oil deterioration occurs and so constant service conditions are maintained over the whole lifetime, the maintenance interval could be extended to 300,000 switching operations, valid for mineral oil as well as for natural esters. An additional benefit of the vacuum technology is the possibility to apply DGA as a diagnostic tool for OLTC health.

5.2 Limitations

Besides the reduced withstand voltages on certain insulation gaps, further limitations have been found, based on extensive testing.

- The switching capacity of change-over selectors is somewhat lower in natural ester, which is mainly due to the higher viscosity. By appropriate tie-in measures, this peculiarity can be covered.
- The specific low-temperature behaviour of natural ester leads to a reduced permissible temperature range. Below a liquid temperature of –10°C, the natural ester investigated begins to solidify, visible by the formation of white clouds. This causes the viscosity to rise rapidly, leading to an inadmissible increase of the switching time of the spring-driven diverter switch.
- Standard gasket material based on nitrile rubber has been found incompatible with ester liquids. The acids in the ester cause the gaskets to become weak and inflexible, which may lead to leakage of the OLTC oil compartment. For applications with ester liquids, gaskets made of fluor polymer rubber should be used instead.

5.3 Hermetical sealing of tap-changer compartment

Due to the fact that natural esters are prone to oxidation, they may only be used in a hermetically sealed environment. Different techniques are available to achieve hermetic sealing. For the OLTC, the same technique as for the transformer can be used. To prevent the tap-changer from inadmissible states, additional equipment is required:

- A sudden-pressure relief device is compulsory to prevent the OLTC from unacceptable overpressure.
- A two-chamber Buchholz relay with flap provides sudden oil-flow detection, leakage detection and release of free gases.

Inside the OLTC oil compartment, gases may be produced by low-energy arcs, occurring at the mechanical contacts due to commutation processes, and additionally by the heating of the transition resistors. The amount of gases produced depends on the OLTC type, the design of the transition resistors and the actual load. In the majority of cases, the gases produced will dissolve in the insulating liquid. Free gases will be produced only in heavy-loaded equipment. These gases accumulate inside a chamber of the Buchholz relay, where they are released to the environment via a magnet valve. This valve is operated automatically by a floater contact of the Buchholz relay.

6 APPLICATION TO HERMETICALLY SEALED POWER TRANSFORMERS

6.1 Measures to avoid moisture and oxygen within the insulation system

Moisture and oxygen within the insulation system accelerates the paper ageing and leads therefore to a reduction of the transformer lifetime. To reduce the thermal de-polymerisation the operational temperature of the transformer can be reduced either by loading the transformer below its nominal rating or by using more material in the physical construction, which finally leads to larger dimensions and at the end to higher cost. The most often used method is the installation of a drying system in the air ducts leading to the expansion tank. These systems only limit the absorption of water. The drying effectiveness strongly depends on the maintenance conditions. Normally 3 to 4 times per year the drying system has to be maintained. In addition these units do not prevent the contact between oil and oxygen.

A more economical way to avoid oxygen within the insulation is to design the transformer hermetically sealed [5, 6]. This technology is well known and has been applied in the market for distribution transformers with expandable corrugated tank walls for a long time. Because of the much higher oil volume for power transformers and the request for vacuum stability of the tank a new concept has to be developed. Expandable radiators are designed to take over the function of the expansion tank, but strong enough that the single sheets of the radiator remain effectively separated during the transformer operation. This strength is necessary to ensure the natural air flow around the radiators for cooling functionality remains sufficient for the generated losses to be dissipated.

The hermetic concept with expansion radiators does not require any air drying system and therefore the maintenance expenditure for the transformer could be reduced. Compared with standard transformers the hermetic power transformer with a vacuum type tap changer has not only the advantage of less ageing it also requires less maintenance for the total lifetime of around 40 years. [7]

It should also be noted that avoidance with moisture contact is also an issue for the bushing requirements, as these cannot be of the design which utilises oil impregnated paper and therefore selection is limited to a range of dry condenser types for higher voltages.

6.2 Oil impregnation of the insulation system

In order to ensure that the insulation system is adequately impregnated for the use of natural esters, significant tests were performed. These tests determined the necessary matrix of vent holes required to ensure sufficient impregnation of the cellulose insulation structures for the specific material thickness required for the voltage class of the transformer design.

The impregnation rate for specific natural esters was found to be around 40 hours at a temperature of 60 ^{0}C for a given sample section of laminated pressboard, which can effectively be translated into many days of processing and impregnation time on a large power transformer. At higher fluid temperatures it was demonstrated that this impregnation time could be reduced.

When preparing a transformer for impregnation, exposure of the ester to oxygen and moisture must be strictly controlled and kept to an absolute minimum, as thin films of the natural ester tend to polymerise much faster than bulk quantities. In order to control this process the internal active part of the transformer requires drying and locating within its tank before final impregnation with the ester.

The limitation of oxygen exposure also applies when draining the fluid from an operational transformer for any reason and, under such circumstances, it is generally recommended that an inert gas, such as Nitrogen, be used to fill the tank to prevent interaction between the thin film of the remaining ester and oxygen prior to refilling operations.

6.3 Hermetic transformers filled with natural ester

Due to the low oxidation stability of natural ester the hermetical sealing of a transformer is a suitable measure to ensure a smooth operation of the transformer by using this environmentally friendly fluid.

The combination of the two measures to extend the lifetime of the insulation of the transformer, avoidance of contact between humidity and transformer oil, as well as the higher ability of moisture saturation of natural esters, will lead to transformers with an extended lifetime. An added benefit is the possibility to overload a transformer for a longer period without a negative impact on the ageing rate. AREVA has developed hermetically sealed power transformers equipped with on-load tap-changers and filled with natural ester Envirotemp FR3. Fig. 7a shows a 40/31,5MVA / 110kV power transformer which is equipped with expandable radiators. Thus no conservator, pipes and breathers are needed. Fig. 7b shows a solution for a 90MVA / 132kV transformer equipped with compensator with rubber bag. Extensive testing of the transformer mounted protection equipment was also performed to ensure operational response times and gas accumulation functionalities were not adversely affected by the viscosity differences from standard mineral oils.

*a) 40/31,5MVA, 110kV +/-16%
equipped with expansion radiators*

*b) 90MVA, 132kV +10%, -20%
conservator with compensator with rubber bag,
picture shows transformer without bushings*

Fig. 7: Power transformers filled with natural ester Envirotemp FR3

7 CONCLUSION

Three natural and one synthetic ester were compared to inhibited mineral oil under new conditions and after ageing. The *water solubility* in natural esters is around 15 times higher than that in mineral oil. The *ageing stability* for the esters and mineral oil was investigated by a heat-accelerated test paying special regard to the oxidation stability. As oxidation processes dramatically increase the viscosity for the natural esters in open systems, an application in open breathing transformers should be avoided. Concerning all other investigated parameters the esters showed similar or better properties than mineral oil.

The investigation of *breakdown strength* for homogeneous field indicates that at moisture saturations typical for transformers the esters perform better than mineral oil. Furthermore moisture has the same influence on breakdown voltage for all fluids. Extensive breakdown tests on on-load tap-changers of various designs reveal that the long gaps behave almost the same as in mineral oil. But certain restrictions in the dielectric strength appeared on special tap-changer electrode configurations.

In order to guarantee an accurate *thermal design*, different material parameters , e.g. viscosity, heat capacity, thermal conductivity and specific gravity, are determined. The temperature distribution in windings was calculated by simulating the oil flow by means of a finite element program based on CFD-Codes (Computational Fluid Dynamics). The higher viscosity of natural ester is adverse for the cooling while the higher heat conductivity is advantageous.

Hermetical sealing is required to avoid polymerisation of the natural ester. Different techniques can be used to achieve hermetical sealing. Special factors have to be considered concerning the design and impregnation of sealed power transformers. Particularly in combination with vacuum type tap-changers, certain limitations apply to ensure operational safety. Compared with standard transformers the hermetic power transformer with a vacuum type tap-changer has not only the advantage of less ageing, it also requires less maintenance for the total lifetime.

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