PROPERTIES OF NEW ENVIRONMENTALLY FRIENDLY BIODEGRADABLE INSULATING FLUIDS FOR POWER TRANSFORMERS

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Abstract:
The problem of using the new environmentally friendly insulating liquids like synthetic and natural esters for power transformers was presented in this article. The positive and negative properties of the esters were described on the basis of a comparison with the most popular insulating liquid like mineral oil. The results of the own experiences and experimental studies were taken into account as well as the results of works presented in the world literature. Conclusions from the analysis indicate that the wide knowledge about ester properties is necessary to correct design process and to proper exploitation of the power transformers filled in esters.

Key Words: Power transformers, insulating fluids, environmental protection, high voltages

Introduction

Power transformers are the one of the most important components of electrical power system serving the transmission and distribution of electricity in the high voltage three-phase electrical power grids and from these grids to the low voltage grids. From this reason, the transformers are the ubiquitous in the human environment. Generally, the transformers are not the devices that generate particularly troublesome environmental problems. However, taking into account the contemporary transformation of public awareness, forcing the pro-ecological look on the each technical device, especially on it, that appears in large number of units in the human environment, it should be searched also for power transformers some new solutions, which improve their ecological properties (Kycior K. 2007, Mosinski F. 2009). A significant majority of the total number of transformers, produced in all ranges of voltage and power, are the oil power transformers. The so-called dry transformers (with resin insulation) are the margin of exploited units. Therefore, in the assessment of environmental risks connected with the transformer in service, the mineral oil is the most important element to be taken into consideration. Of course, the aspects such as the risk of electric shock, noise and vibration as well as energy and power losses are also important, but taking into account the effects for the environment from these types of interactions, these, connected with mineral oil, seem to be the most dangerous (Kucharska A. 2007, Mosinski F. 2009).

Mineral oil is a mixture of different kinds of hydrocarbon compounds (naphtenic C_nH_{2n}, such as cyclohexane C_6H_{12}, paraffin C_nH_{2n+2}, such as hexane C_6H_{14}, and aromatic C_nH_n, such as benzene C_6H_6). The proportions of the contents of the individual components depend on the composition of the starting petroleum and, for example, most prized naphthenic transformer oils can be obtained only with the certain types of petroleum. Therefore, in the case of spillage of oil to the environment, the oil is not a neutral for it. Additionally its amount (exemplary in the oil power transformer having the nominal voltage 110 kV the mass of oil is about 7-8 thousand kilograms, while in the transformer 400 kV such mass is nearly 80 thousand kilograms) intensifies the hazard. Commonly used mineral transformer oil has an ecological threat index twice higher than water, but it concerns the fresh oil without any polychlorobiphenyls admixtures (PCBs). The aged oils (those derived from the long-operated transformers) may, however, contain significant quantities of polycyclic aromatic compounds (benzene, toluene, xylene), which have a carcinogenic properties. Ecological threat index can then be increased up to the three times in comparison with fresh oil. Generally, in the case of transformer failure, the mineral oil leaked to the soil may be the source of its contamination (degradation of oil-soaked layer), and in consequence also the contamination of water bodies and flora and fauna, which is in the area of contaminated space. Due to the relatively high solubility in water, the hydrocarbon compounds can migrate with infiltrating rainwater by the aeration zone to the first aquifer. For example, 1 kg of the waste oil that has leaked from the transformer to the water reservoir makes it unfits to drink in the volume of 5 million liters (Kucharska A. 2007, Mosinski F. 2009). Numerically, the measure of a potential contamination of the given fluid is determined by the level of its biodegradability. For mineral oil, this factor is very low, and in accordance to the OECD 301 standard, is only 10%. It means that after 28 days from the entering the oil to the environment, only such small part of this fluid surrenders to self degradation. Thus, the failures concerning the oil leakage are undoubtly harmful to the environment (air, water, soil), and the costs of removing their effects are usually very large. Prevent them or limitation their effects, although expensive, has an importance meaning for the environment. It is believed that this role is fulfilled by the special place with the pans for leaking oil, by the systems of oil and water separation, and by the monitoring of the transformer and its equipment (Mosinski F. 2009, Rozga P., Skowron A., 2012). The example of the oil pan installation is shown in Fig. 1.

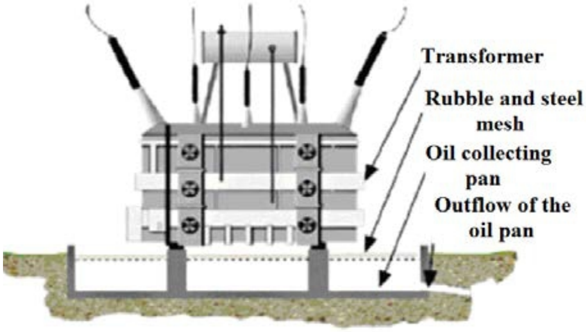

Fig. 1. Example of the oil pan installation.

The volume of designed and built oil pans should be sufficient to bring all of the oil contained in the transformer. In the cases where the transformers are equipped additionally with the water sprinkler systems, the volume of the pan is increased by an additional 10-20%.

Mentioned on the beginning of this chapter the problem of PCBs is now generally margin. Currently used transformer oils meet the criteria for the PCB content, which, in accordance to the specified requirements, should be less than 50 ppm (Kaminska A. 2007).

Another problem of environmental nature is the combustibility of mineral oil due to its relatively low flash point. Combustion products of mineral oil being the result of its ignition occurred because of transformer failure (e.g. short circuit), are considered to be dangerous and cause air pollution. 1000 kg of burnt, under unfavorable conditions, mineral oil emits circa 10 kg of harmful substances to the atmosphere. Additionally, the side product accompanying the mineral oil combustion is the dense and very black smoke (Fig. 2).

Fig. 2. Example of transformer failure with fire

Therefore, one of the pro-ecological solution, which is connected directly with the use of mineral oil in power transformers, is to replace it by a new environmentally friendly insulating liquids produced on the basis of natural and synthetic esters, which importantly decrease the negative influence of the transformer on the environment (Oommen T. V., Clairborne C. C., Mullen J. T. 1997, Borsi H., Gockenbach E. 2005, Martins M. A. G. 2010). Such alternative is necessary, especially in the areas having highly restricted regulations concerning the environmental protection and fire prevention. The pro-ecological liquids, from the environmental protection point of view, are characterized by the high level of biodegradability reaching even 95%, and from the fire prevention point of view, have the significantly higher than mineral oil flash point (above 300 ^{O}C to circa 140 ^{O}C characterizing the mineral oil).

It is however important, that in spite of the good ecological properties of esters, they can bring many problems, especially in the phase of design and manufacture of transformers, what resulted from the short time of existing the esters on the transformer market, and incomplete knowledge in this field. Therefore, the properties of new, environmentally friendly electro-insulating liquids will be presented in comparison to the analogical properties of mineral oil. The comparison will be based on the fundamental experimental studies (also author's).The similarities (mainly in the field of electrical strength) and the differences (in the behavior of liquids in the heating process, in the field of lightning strength, in the field of chemical parameters) will be presented and critically discussed.

The problem of using biodegradable liquids in power transformers

Environmentally friendly insulating fluids, which are an alternative to mineral oils, are the synthetic esters and natural esters, for which the base are vegetable oils produced from canola, soybean, corn etc. In Fig. 3, the molecular structures of two commercial dielectric liquids - natural and synthetic ester are shown.

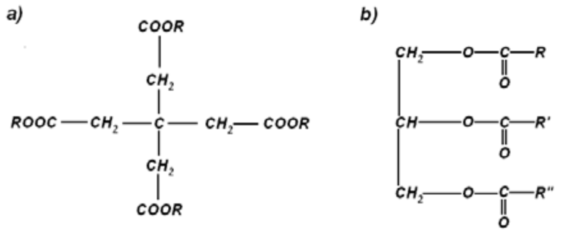

Fig. 3. The chemical structures of synthetic ester (a) and natural ester (b); R, R', R'' – organic groups.

Both liquids have been more than ten years in the test phase, and prototype units filled by these fluids are with nominal voltages up to 238 kV and above 100 MVA in capacity. Natural ester is an ester based on soybean oil. The major molecular component of this ester is mixed triglyceride built from the glycerol molecule and three molecules of long chain fatty acids linked together by ester bonds. In a one triglyceride molecule may be a variety saturated and unsaturated fatty acids consisting even from the 22 carbon atoms in the chain. The synthetic ester is an organic synthetic chemical compound - pentaerythritol ester, which consists of four ester groups -COOR which are at the end of the cross structure of the compound, and in which the organic groups R may be either the same or different.

In the Table 1, the basic physico-chemical and dielectric parameters for both esters and mineral oil are summarized (FR3 Data Sheet 2008, Midel 7131 Data Sheet 2010). These parameters concern the fresh fluids as received by the manufacturers, without the use of any treatment.

Table 1. Basic parameters of synthetic ester, natural ester and mineral oil.

	Units	Synthetic ester	Natural ester	Mineral oil
Physico-chemical properties				
Density at 20^{O}C	kg / dm^3	0,97	0,92	0,88
Specific Heat at 20^{O}C	J / kg K	1880	1848	1860
Thermal Conductivity at 20^{O}C	W / m K	0.144	0.177	0.126
Kinematic Viscosity at 20^{O}C	mm^2 / s	70	85	22
Kinematic Viscosity at 100^{O}C	mm^2 / s	5.25	8.4	2.6
Pour Point	^{O}C	-60	-21	-50
Fire Point	^{O}C	316	360	170
Flash Point	^{O}C	260	316	150
Fire Hazard Classification to IEC 61100 / IEC 61039	-	K3	K2	0
Biodegradability	%	89	97	10
Dielectric properties				

Breakdown Voltage	kV	> 75	> 75	70
Dielectric Dissipation Factor Tg δ at 90^{O}C	-	< 0.008	< 0.003	< 0.002
Permittivity at 20^{O}C	-	3.2	3.1	2.2

As was mentioned above, among the main physico-chemical properties of the esters, particular meaning, from the side of ecological aspect, has two of them: biodegradability and flash point. For both of esters, their biodegradability is significantly higher than mineral oil, what confirms the better ecological properties of these liquids. Taking into account that after 28 days both of esters decay in above 60%, according to the OECD 301 standard, they can be admitted as a biodegradable. Thus, using esters in the places having restricted environmental regulations is not a problem. It is important to notice, that in the case of esters it is not necessary to use the oil pans, what finally reduces the costs of installation of the transformers.

The second of the mentioned parameters – flash point – also specifies the esters as the environmentally friendly liquids. Performed for the all three insulating fluids the test of "open burner" indicates on the flash temperatures identical as determined by the manufacturers in the data sheets. For the mineral oil the temperature, after delivered the open fire from the acetyl burner, rose violently and after 4 minutes the ignition of mineral oil took place in the temperature of about 130 ^{O}C. Then the oil burned without the open fire and during the combustion process emitted the dense black smoke. Whereas in the case of ester fluids the temperature rose slower and after the 70 minutes the process was stopped because the ignition did not occur and the temperature reached nearly 300 ^{O}C. The better properties of esters are also visible looking at the intensity of the smoke emitted by the burned liquids. In the case of mineral oil smoke is black and very dense while for the both esters smoke is emitted in the smaller amounts and its dense is also much lower. In percentages, the volume of waste gases emitted by the burned esters in relation to the gases emitted by burned mineral oil is only about 15%.

From the insulating properties point of view the most important parameter is breakdown voltage. This voltage, according to the IEC 60156 standard, is determined by the introduction of the liquid sample to the special apparatus with profiled metal electrodes creating the uniform electrical field distribution and then subject to the rising electrical field resulting from the AC voltage increasing. The average value of six breakdowns occurring in the specified conditions is taken as an AC breakdown voltage. Of course, the value of breakdown voltage depends on the quality of tested liquid (water and impurities content), so in order to compare the values of breakdown voltages of different dielectric liquids, they should have the similar quality (Li J., Grzybowski S., Sun Y., Chen X., 2007, Dang Viet-Nung, Beroual A., Perrier C. 2011). In the Fig. 4, the results of the measurements of AC breakdown voltage are presented. These results confirm identical properties connected with the electrical strength of synthetic ester, natural ester and mineral oil.

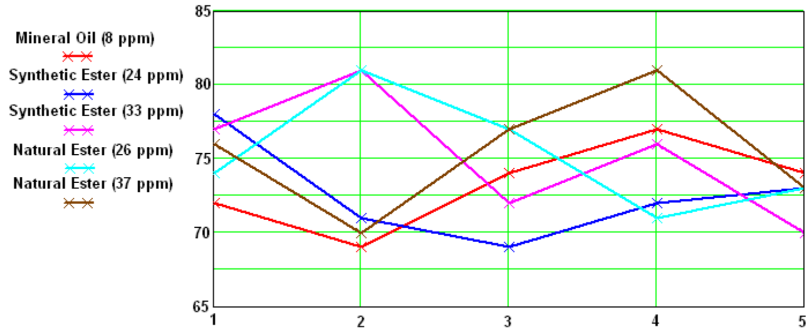

Fig. 4. AC breakdown voltage for different types of insulating liquids measured according to the IEC 60156 standard.

Looking at the influence of moisture content on the electrical strength, the esters behave more favorable. It is because the esters are characterized by the constant value of breakdown voltage apart from the moisture content up to 600 ppm (Martins 2010, Dang Viet-Nung, Beroual A., Perrier C. 2011). For the mineral oil, its strength goes down even at the small increasing of moisture (at 20 ppm the breakdown voltage is only 40 kV while for good conditioned oil this value is in the range of 65-75 kV).

Similarly other parameter characterizing the dielectric properties of the liquids, that is the electrical permittivity, also indicates on the possibility of better using the esters in the insulating systems of power transformers. The insulating systems of the transformer windings are usually a combination of electro-insulating fluid and solid insulating materials like paper or transformerboard. These systems are series, series-parallel or parallel. In the series systems, which are the most often systems in the transformers, the distribution of the stresses is inversely proportional to the electrical permittivity of the materials created it. The system has a higher strength if the more uniform stress distribution is. The higher value of electrical permittivity of the esters (3.1-3.2) than the mineral oil (2.2) thus influences profitable on the stress distribution in the system: electro-insulating fluid – cellulose (electrical permittivity of cellulose is 4).

Although there are many positive properties of the biodegradable esters concerning the electrical strength at AC voltage, their lightning strength, that is the strength for a short voltage pulses having steep front (1.2 µs) and long back (50 µs), is not as good as in the case of mineral oil. The studies on the mechanism of initiation and propagation of electrical discharges developing under above mentioned lightning pulses indicated that only at inception voltage or at the 50% breakdown voltage, the discharges developing in the same way independently on the type of dielectric liquids. When the voltage increases, thus, when the voltage multiplicity in relation to the 50% breakdown voltage rises, the discharges, both in the natural and synthetic esters stands more energetic and at the lower than in the case of mineral oil overvoltages, the developing of discharges in esters is determined by liquid phase ionization. More energetic discharges are more dangerous for the solid insulation of the transformer (paper and transformerboard) causing its damage in the form of local carbonization. Therefore, when the one of the esters is used as an insulating medium, it is indicated, for the sake of lightning strength, using the wider insulating gaps in the transformer. It is particularly important in the case of big transformer units having the rated voltages equal or higher than 110 kV (Tran Duy C., Lesaint O., Denat A., Bonifaci N. 2009, Liu Q., Wang Z. D. 2011).

One of the negative properties of the esters, but without any direct influence on the possibility of using esters in power transformers, is the susceptibility on the action of concentrated heat flux (Rozga P., Skowron A. 2012). This property was observed during the process of preparing of the esters for the filling the transformer, and then confirmed by the laboratory measurements. The experimental studies indicated that the influence of the heating elements, used in the heating process of the esters, determined by the unitary surface load expressed in W/cm^2, causes the growth of the dielectric dissipation factor tgδ of the esters. This growth, at the value of unitary surface load identically as used during the heating process of the mineral oil (2 W/cm^2), is such meaningful, that tgδ of the esters exceeds the boundary values determined in the standards although the fluids were not exploited. The exemplary curve presenting the dependence of the tgδ versus unitary surface load for synthetic ester, performed during experimental works, was shown in Fig. 4.

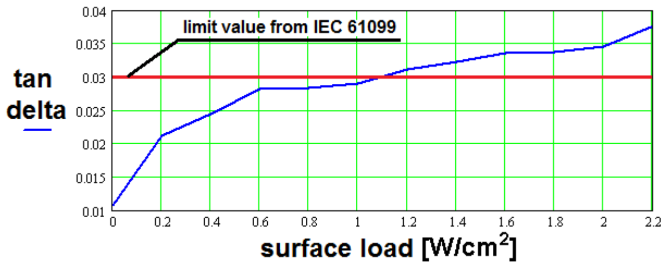

Fig. 5. Dependence of dielectric dissipation factor versus unitary surface load for a synthetic ester.

The described phenomena do not concern mineral oil. Its treatment does not change the dielectric properties of mineral oil. The differences in the different behavior of esters and mineral oil result from the different physico-chemical properties, which directly influence on the phenomena occurring during the heating. In the case of mineral oil, the laminar flow of the oil, because of its relative low density and first of all low viscosity, is relatively fast. Thanks to it, the oil reminds in the direct contact with the surface of the heater only by the short time. In the case of esters, which are characterized by the much higher density and viscosity, contact with the surface of the heater is much longer. It causes that the layers of the liquids "stick" to the surface of the heater and their overheating taking effect of disintegration and decomposition of molecular bonds. Finally, in the liquid volume the polar particles appear and growth of above mentioned dielectric dissipation factor takes place. Taking into account the large experience in the filed of mineral oil treatment and lack of precisely defined parameters of the heating process of the esters, the presented problem is quite significant from the production phase point of view. For the esters the production process becomes lengthen because similar heating conditions as for mineral oil is not possible to keep.

The higher density and first of all the higher kinematic viscosity of the esters is also important at the consideration of their influence on the transformer cooling conditions. Generally, the working transformer generates the energy losses. These losses are in the windings, in the magnetic core and in the metal elements of the construction. The losses transform in the heat, what causes the heating of the individual parts of transformer. The requirement for the good work of transformer is the effective heat abstraction outside it. The mechanism of the heat abstraction looks as following: the heat arising in the individual internal parts of transformer gets out of its (heat conduction); from where with the usage of the cooling medium (electro-insulating fluid) is directly or indirectly carried away to the surroundings. The higher kinematic viscosity of the insulating fluids is, the better the cooling function is fulfilled. Additionally, the kinematic viscosity, both for esters and for mineral oil, depends on the temperature, what was presented in Fig. 5. However, the mineral oil has a viscosity much lower and because of it, it seems to notice that mineral oil fulfils better the cooling functions in the power transformer than biodegradable esters.

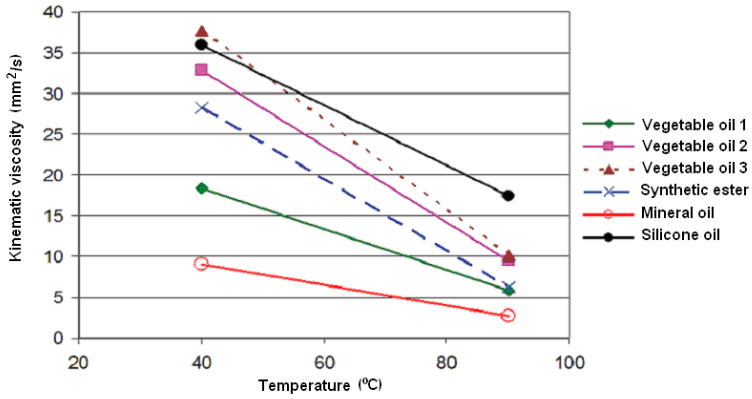

Fig. 5. Dependence of kinematic viscosity versus temperature for selected dielectric fluids.

From the other hand, the higher density of esters causes that these liquids do not circulate as freely and with the proper flow velocity in the narrow cooling channels of the windings and magnetic core as mineral oil. Flowing ester cannot reach all fragments of the insulating systems of transformer windings. Thus, the construction of insulating system of power transformer filled by ester should take into account its physico-chemical properties in order to provide the correct circulation of the cooling fluid both in the natural and forced circulation. Hence the systems forcing the liquid circulation in the transformer filled by ester should be characterized by higher power, and the oil channels should be wider than in the case of transformer with mineral oil (Hulshorst W.T.J., Groeman J.F. 2002, Pukel G. J. 2009, Martins M. A. G. 2010).

Conclusion

Biodegradable synthetic and natural esters are the good alternative for mineral oil, especially in the situations when the power transformer has to be installed in the places for which the restricted environmental regulations are specified. Next to the many positive aspects like the higher biodegradability, high flash point and good properties concerning the AC electrical strength, esters have also negative features, which should be taken into account in the design phase and during the exploitation of the transformer with esters. The parameters of the designed transformer must be based on the knowledge about these negative features. Designer should know that the esters are susceptible to the action of a concentrated heat flux, have the worse cooling properties than mineral oil, and lower lightning strength. The final product – power transformer filled by ester – will be in effect the more expensive device, but taking into consideration the pro-ecological tendencies reigned on the transformer market and still increasing demand for new environmentally friendly products, in the feature the cost will be certainly lower.

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