

Alternative Fluids – with a Particular Emphasis on Vegetable Oils – as Replacements of Transformer Oil

A Concise Review

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Abstract-For many decades transformer oil has served as a well-known insulating medium. Its electrical properties, among others, have been studied in length. In recent years, with the increasing concern for the environment, alternative insulating liquids have been proposed. In the context of this concise review, such alternative fluids are investigated. Some conflicting evidence regarding experimental results that still persist are discussed and aspects of vegetable oils in need of further work are pointed out.

Keywords-alternative fluids; vegetable oils; transformer oil; mineral oil; dielectric strength; breakdown voltage; oxidation; fluid viscosity; cooling function; flash point; fire point

I. INTRODUCTION

During the last decades, transformer oils, consisting of a mixture of hydrocarbons including paraffins, isoparaffins, naphthenes and aromatics, have enjoyed extensive use [1]. Such a liquid undergoes aging depending on its exposure to prolonged heating and electrical stresses. Aging of transformer oil results to gradual change in its electrical and thermal properties, i.e. a change in color and a formation of solid byproducts. Transformer oil, although an excellent insulating medium, has also its weak aspects, such as its sensitivity to humidity (it has been reported, for example, that oil at 20°C with water contents of 44ppm will have only 25% of its normal dielectric strength [2]). Various studies have been carried out regarding the properties and aging of transformer oil, such as the dielectric strength, the humidity content, the role of air bubbles on its electrical behavior, the variation of dielectric constant and density w.r.t temperature etc. [3-7]. In [8], a comprehensive review was given regarding the properties and applications of a variety of insulating liquids. In that review, except the transformer oil, there were comments on silicone oil, fluorinated liquids, chlorinated and phosphate fluids, and ester and synthetic hydrocarbons. Polybutene liquids were also mentioned as possible substitutes to transformer oil, especially regarding the dielectric strength [1, 9] (in fact the DC dielectric strength of some polybutene oils was found to increase with increasing liquid density up to 65MV/m at a density of 880kg/m³ as compared to untreated transformer oil under the same conditions). The mechanisms of breakdown in transformer oil have been thoroughly studied [10-12]. Moreover, efforts have been made to improve the general

electrical performance of transformer oil by adding minute quantities of certain substances, as has been reported in [13-16]. Furthermore, the state of transformer oil has been investigated with classical diagnostic techniques [17], as well as with more modern diagnostic techniques [18].

Although transformer oil has served satisfactorily the high voltage industry for many years, it became evident that there were some less positive aspects about it, such as its inflammability and the fact that it is not biodegradable. The aim of the present paper is to give a concise review of some alternatives to transformer oil and comment on their various aspects. It is evident that in the context of the present review there will be no mention of nanofluids [19, 20]. It must be emphasized that the present short review does not by any means include all possible alternative fluids to transformer oil since only vegetable oils are particularly mentioned and discussed.

II. EARLIER PROPOSALS FOR ALTERNATIVES TO TRANSFORMER OIL

Earlier attempts to replace transformer oil with other liquids are reported in [8]. Ester hydrocarbons can be chemically tailored so as to produce high thermal stability or fire resistance if used in transformers [8]. Polybutene oils were reported as having certain advantages regarding their dielectric strength in comparison to transformer oil [1, 9, 21]. Moreover, polybutene oils present, among others, high fire resistance and heat dissipation as well as arc discharge quenching [22]. Silicone fluids further enhance the thermal stability properties [21]. They are fire resistant but - at least at the initial stages of their development - they suffered from poor heat transfer [23]. As noted in a later publication [24], silicone fluids w.r.t. their cooling and insulating properties, compare reasonably well with mineral oils. Silicone oils are environment friendly with a strong resistance to oxidation and sludge formation, but they are rather expensive and they have high viscosities at 200°C [25]. Fluorinated oils may be excellent insulating liquids but were expensive with a questionable effect on the environment [8]. Polychlorinated biphenyl (PCB)-based insulating liquids, although they have high fire security standards, they proved to be a liability because of their toxicity and their bioaccumulation [8, 21, 24, 26-28]. Phosphate esters were

another alternative because they were relatively cheap. They were, however, more destined as lubricants and rather poor insulants [29]. Questions also have been raised regarding their environmental hazards [8].

Other approaches for alternative liquids, such as electronegative fluids or liquefied elemental gases will not be mentioned here, since the former played more the role of refrigerants, and the latter were destined for use in superconducting magnets in high energy particle machines [8]. Moreover, the subject of liquefied gases was partially dealt with in a recent review publication [30].

III. FACTORS THAT MAY INFLUENCE THE BEHAVIOR OF INSULATING LIQUIDS

As was noted in [8], transformers require a fluid which has both good insulating properties and which can also be an efficient coolant. Low loss tangent and high resistivity are also required. The fluid must be non-flammable, non-toxic and biodegradable. Low gas absorption and low expansion coefficient must also characterize a transformer fluid. The fluid must be – as far as it is possible - free of impurities (dust, fibers, and metallic particles) and its gas content should be as small as possible. Gas bubbles may enhance electron emission and cause premature failure and thus should be avoided [31]. Since in a liquid filled system such as a transformer, heat is transferred mainly by convection, the thermal conductivity of the fluid is of primary importance [8]. The temperature effect is a complex phenomenon because of the possible changes in cathode emission, gas content and fluid viscosity [31]. Let us not also forget the interplay between moisture and temperature, since it has been reported that oil having small amounts of moisture showed an increase in dielectric strength, whereas the opposite effect was observed with dry oil [31]. Viscosity is another significant parameter in determining the heat flow in a transformer. As temperature increases, the fluid viscosity rapidly falls and consequently the cooling effect is greatly enhanced [8]. Needless to say that big differences may exist between new and aging oil, as has been reported previously, especially regarding the dissipation factor and the dielectric strength, and this is the reason of periodic control of the oil quality and – if need be – its replacement [32-34]. Yet another vital parameter is the resistance of the fluid to discharges. This, however, depends on the nature of the fluid. Other insulating liquids release gas bubbles, whereas others absorb gas bubbles, as was noted in [8, 35]. Besides the factors, it would be fitting to add that for some of the liquids mentioned above, there are serious objections. Fluorinated oils, for example, have a high cost, so that their use is rather prohibitive [36, 37]. Polybutene oils, although non-toxic and environmentally friendly with rather satisfactory flash points, are rather expensive for use in large volumes [24].

IV. POSSIBLE ALTERNATIVES TO TRANSFORMER OIL: MODERN APPROACHES

Silicone oil, synthetic ester and natural ester oils are possible alternatives to transformer oil. Silicone oils, however, besides some problematic aspects as mentioned above, are still highly viscous at higher temperatures and present limited biodegradability [38]. As noted in [24], in order to avoid large

temperature rises during operation, silicone-filled transformers must be de-rated (up to 10%) or provided with additional cooling capacity. On the other hand, synthetic esters are usually derived from the combination of more than one alcohol functional group (polyol) with carboxylic acids leading to a central polyol structure. Most preferably the synthetic ester is defined as a family of polyol esters and in particular these fluids are pentaerythritol tetra ester as shown in Figure 1.

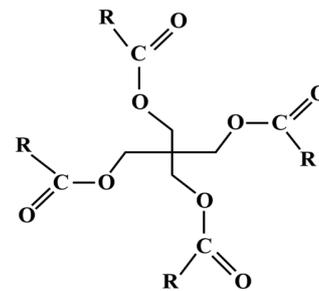


Fig. 1. Structure of synthetic ester.

where R represents an alkyl group ranging from C_5H_{11} to C_9H_{19} . Synthetic esters present high oxidation stability, have a very good cold temperature performance and are easily biodegradable [38]. Synthetic ester liquids can absorb significantly more moisture than transformer oil before their insulating properties deteriorate [24]. Tetraesters (or pentaerythritol esters) are environmentally friendly but they are expensive. Tetraesters can absorb moisture produced by thermal degradation of cellulose (paper) present in the windings, their viscosity, however, is higher than that of transformer oil [24, 39]. In [39], it is noted that the high saturation limit of such liquids (many times higher than that of mineral oil) reduces the moisture content in the solid insulation due to water diffusion into the liquid, having better insulating performance as a consequence. It should also be pointed out that the higher moisture content implies the formation of free fatty acids [24]. The higher absorption of moisture of tetraester fluids is due to their carbonyl structure, as reported in [40]. Phosphoric esters have high fire point and permittivity. In certain aspects, such as breakdown voltage, dissipation factor and resistivity, they are supposed to be comparable or even better than mineral oil, but they tend to also have some negative aspects because they pose some environmental risks [24, 41]. Because of the latter, their use is rather limited.

Natural ester consists of a glycerol backbone with different fatty acid groups and it can be saturated, mono unsaturated, and poly unsaturated. Vegetable oils can easily be obtained from natural products and are considered reasonable replacements of transformer oil. As was noted in [24], they consist essentially of triglycerides (Figure 2), which are naturally synthesized by the esterification of the tri-alcohol glycerol with three fatty acids. One of the aforementioned oils is castor oil, which is a vegetable oil from the castor bean. It is colorless to very yellow pale with mild or no odor or taste. Its boiling point is $313^{\circ}C$ ($595^{\circ}F$) and its density is 961kg/m^3 . It is a triglyceride in which approximately between 87% and 90% of fatty acid chains are ricinoleic acid [42]. It was found in the same

publication, however, that the dielectric strength of castor oil is not as good as that of transformer oil. The results of [42], were somehow contradicted in [43], where it was shown that castor seed oil gave breakdown values that were comparable (but not superior) to those of transformer oil. On the contrary, castor seed oil's flash point, pour point, and viscosity were found to be better than those of the transformer oil. In yet another publication, castor oil was blended with madhucaindica oil and the mixture showed to have satisfactory heat transfer, pour point, flash point, and viscosity compared to transformer oil but its dielectric strength was found to be lower than that of transformer oil. The authors concluded that such a blend can work for low but not for high voltage transformers [44]. They remarked, however, that with more refinement this blend can also be used for high voltage transformers.

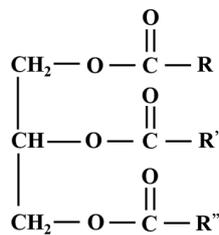


Fig. 2. Structure of natural ester.

In Figure 2, the structure of natural ester is depicted, where R, R', and R'' refer to the different alkyl groups with a major variation in the number of C=C double bonds. The chemical composition of different fatty acid groups (Table I) determines the physical properties of the oil, i.e. with higher amount of saturated acids in the ester group, the fluid is more stable towards oxidation and less viscous compared to unsaturated acids which makes them unstable [45].

TABLE I. FATTY ACID COMPOSITION OF VEGETABLE OILS

Oil fatty acid	Saturated fatty acid		Mono-unsaturated	Poly-unsaturated
	Palmitic acid (C16:0)	Stearic acid (C18:0)	Oleic acid (C18:1)	Linoleic acid (C18:2)
Palm	45	4	40	10
Olive	11	3	71	10
Rapeseed	4	2	62	22
Sunflower	7	5	19	68
Soyabean	11	4	24	54

Vegetable oils were investigated in [46], where their advantages and disadvantages were treated accordingly. It was remarked that vegetable oils are susceptible to oxidation, and thus hermetic sealing is required in order to ensure optimum performance. The use of vegetable oils in transformers – because of their higher viscosity - results in increased temperatures of between 10 and 30°C. The higher viscosity, however, has also its positive aspect since it implies reduced spread in case of spillage conditions. On the other hand, their pour point is satisfactory, they are classified as low flammability liquids, their breakdown voltages tend to be much higher than those of mineral and silicone oils even with

substantial amounts of moisture, and, last but not least, the operating temperatures of vegetable oils are clearly higher than those of mineral oils. The latter point of [46] is contested in [47], where it was claimed that in the case of power transformers (e.g. 160MVA) temperature increase in transformers filled with esters can be even greater as compared to the temperature of the transformer filled with mineral oil. Therefore, according to [47], in order to use synthetic or natural ester, the changing of the geometry of the transformer (increasing its size), the reduction of the load, or the modification of the cooling system should be considered.

Another perspective on vegetable oils was given in [48], where soya bean oil and palm kernel oil were investigated. The authors concluded that both aforementioned oils can be used as replacements for mineral oil on the condition of refinement since they possess a lower dielectric strength and they hold more moisture than mineral oil. The viscosity of both oils is higher than that of mineral oil and their flash point is much higher than that of mineral oil. The authors seemed to reluctantly propose both vegetable oils as replacements of the transformer oil on the condition of further purification. Authors in [48] seem to agree with the results published before, where mineral oil was compared with vegetable oil and synthetic ester oil in the presence of pressboard [49]. In [49], Partial Discharge (PD) levels were found to be higher in both alternative oils than in mineral oil. Although no specific reason was given for such differences in the PD level, [49] was an effort to investigate solid/liquid insulation as is used in transformer windings. Although there was some skepticism, as reported above, there were other publications that suggested the use of vegetable oils, since these presented a dielectric strength comparable to that of mineral oil and the saturated fatty acid content in such oils retarded the deterioration of the insulating fluid in high-temperature environments or long-term storage conditions. Moreover, vegetable oils showed more cooling ability and high insulation capacity than mineral oil [50]. Authors in [51] agree with [50], reporting that while oxidation of mineral oil produces sludge precipitates, vegetable oils are much more resistant to oxidation.

Vegetable oils have been researched in [52], where the authors carried out a detailed study of Rice Bran Oil (RBO), Corn Oil (CO) and transformer oil. Their investigations indicated that when the viscosity of transformer oil is lower than those of RBO and CO, the flash point and the fire point of the vegetable oils were much higher than those of the transformer oil, with the dielectric strength of RBO being higher than that of transformer oil. All in all, the authors of [52] concluded that, because of the rich content of fatty acids, vegetable oils – and particularly RBO – give enhanced performances compared to the transformer oil. RBO was also investigated in [53] along with with sesame oil, sunflower oil, and mineral oil in a comparative study. RBO was superior to the other examined oils regarding the flash point (but not the fire point, where sesame oil was found to be superior), the breakdown voltage and the viscosity. The oxidation stability of the aforementioned vegetable oils, however, was not as good as that of the mineral oil. The latter statement on oxidation stability is in agreement with [54, 55], where it was reported that olive oil offered excellent resistance to aging, rapeseed oil

offered intermediate properties whereas corn and sunflower oil oxidized appreciably after aging. Authors in [55] reported that partial discharge magnitudes of Palm Fatty Acid Ester (PFAE) are slightly lower than those of petroleum-based mineral oil during the aging time, which somehow contradicts the findings in [49]. In [56], the authors investigated the problem of dielectric strength of mineral oil, corn oil, sunflower oil, and rapeseed oil from another viewpoint, namely that of statistical analysis. They found that for the above mentioned oils and with plane-plane electrodes, the vegetable oils had a higher mean dielectric strength than mineral oil. A later work [57], pointed out that the AC dielectric strength of the synthetic ester oil and the natural ester oil were higher than the dielectric strength of mineral oil as moisture was increasing. In the same work, the impulse dielectric strength of the vegetable liquids seemed to be less affected than that of mineral oil. It should be noted, however, regarding PD activity, both palm oil and corn oil showed a lower activity than mineral oil with a rod-plane electrode arrangement at 25 kV, especially after thermal aging of 30 and 45 days [57]. The PD results of [57] are in disagreement with the results of [49].

Coconut oil was the exclusive subject of [58], where it was claimed that its dielectric strength with both mushroom and spherical electrodes was satisfactory. The authors studied the variation of its dielectric strength w.r.t. moisture content but they did not compare coconut oil with mineral oil. Their claim, however, that coconut oil can be an alternative to transformer oil was supported from an earlier publication [59], where coconut oil was shown to have higher dielectric strength than transformer oil, having also a much higher flash point. The experimental results of [58] are in accordance with those of [60], where coconut oil was found to be even superior to refined, bleached, deodorized palm oil (RBDPO). Further detailed studies with soybean oil, coconut oil, palm oil and rice husk oil revealed that all of them have higher flash and fire points than mineral oil, with coconut oil, palm oil and rice husk oil having also higher breakdown values than mineral oil [61]. Soybean oil was found to be no better than mineral oil regarding breakdown voltage. In that, reference [61] was at variance with the data presented in [48]. The experimental results of [61] deviate significantly from those of [62], where a surprisingly very low dielectric strength for coconut oil was observed in comparison with mineral oil. No specific explanation was given by the authors of [62] for such low dielectric strength values of the coconut oil. Coconut oil has indeed lower dielectric strength than virgin coconut oil and palm oil [63], but not as low as that reported in [62]. On the other hand, there have been earlier reports mentioning the rather low dielectric strength values of coconut oil in comparison to transformer oil [64], but not as low as those of [62]. Yet again, such data are contradicted from recent experimental results suggesting that the dielectric strength of coconut oil is very similar to that of mineral oil [65].

Recent studies showed that vegetable oils are possible replacements for mineral oil [66]. The authors in [66] investigated a variety of vegetable oils, such as corn oil, castor oil, olive oil, and ester oil. Especially the dielectric strength of corn, castor, and olive oils was higher than the dielectric strength of mineral oil. The authors concluded that such

vegetable oils can replace mineral oil in power transformers. In [67], both the positive and negative aspects of vegetable oils have been discussed. The author remarked that, besides the positive aspects – which have been referred to also above –, there are also some negative aspects of vegetable oils, namely that their cooling function is not as good as that of the mineral oil and the dielectric strength under lightning voltages is inferior to that of the mineral oil. Furthermore, and in relation to kraft paper, the positive and negative aspects have been discussed in [68]. Others reported that higher rates of water migration from paper to the oil was observed during heating of natural ester oil in comparison with mineral oil [69]. In a further publication it was reported that the kraft paper/mineral oil combination lowered the Degree of Polymerization (DP) index, defined as the average number of repeating units that are contained in the molecular chain of a polymer, even more than the kraft paper/vegetable oil combination [70]. The authors of [70] used two vegetable ester-based oils without, however, giving full details about them. Agreeing with [70], another work reported that testing with *Jatropha curcas* oil, the latter's combination with kraft paper gave a rather satisfactory DP. Moreover, the refining process of *Jatropha curcas* oil, although it did not influence the physical properties of density, viscosity, and fire point, it improved somehow its flash and pour points giving also a very satisfactory dielectric strength [71]. It has to be noted, however, that without antioxidants, *Jatropha curcas* oil tends to be considerably oxidized during accelerated aging [72].

The better cooling function of mineral oil in comparison to vegetable oils has also been reported in [73]. In the latter publication, however, emphasis was given on other aspects of vegetable oils, such as their rather satisfactory AC dielectric strength, high biodegradability, and fire safety. Of the vegetable oils tested, RBDPO was found to have a high breakdown voltage and low dissipation factor among the other candidates (soybean oil, sunflower oil, rapeseed oil, coconut oil), and thus it was suggested as the best alternative fluid to mineral oil. Other researchers, however, reported that extra virgin olive oil and castor oil have very high dielectric strengths [74]. Extensive work on soybean-based oil revealed that it releases more ethane than mineral oil, whereas the Dielectric Dissipation Factor (DDF) is normally higher for a vegetable oil than for a mineral oil [75]. Experimental work on rapeseed oil revealed that its dielectric strength is comparable to that of mineral oil [76], and that it can be used for power transformers, especially if improved through the use of an antioxidant [77].

V. CHALLENGES INVOLVED WITH ALTERNATE FLUIDS FOR TRANSPORT APPLICATIONS

The higher thermal class of ester fluids makes them viable in densely populated areas or commercial buildings such as shopping malls and airports. Further, the transformers filled with such liquids can be placed closer to the buildings which benefit from its reduced equipment spacing requirements as specified in the National Electrical Code (NFPA 70). When comparing the installation of transformers containing ester fluids with existing mineral oil, it also provides additional benefit of shorter Low Voltage (LV) cable runs and hence

lower losses. The ester fluids are hygroscopic in nature, so precautionary measures on storage and handling such liquids must be taken care of in order to prevent their reaction with atmospheric moisture and hence these liquids are recommended in non-breathing transformers. The relative permittivity of any dielectrics affects the electric field distribution in the winding structures and must be considered before the use of new alternate liquids inside the transformers, where the stress exerted at the oil/pressboard interface is very low on the usage of ester fluids due to its minimal variation in permittivity. Also, the fluid flow characteristics along with thermal modeling of windings must be considered before designing in order to evaluate the difference in temperature rise for an ester filled transformer, compared to standard mineral oil.

VI. SOME THOUGHTS ON FUTURE RESEARCH

Interest in vegetable oils was noted a long time ago [78, 79]. Excellent reviews have been published on alternative fluids to transformer oil [80]. Without doubt, vegetable oils can be a hope for the future replacement of mineral oil in power transformers. There are, however, efforts to be undertaken in order to clarify certain pending issues. Some conflicting data reported above must be further looked upon and further experiments should be carried out. There is still some uncertainty regarding the dielectric strength of some vegetable oils as well as their PD behavior [81, 82]. Further research should be directed towards this goal. The weakness of vegetable oils w.r.t. lightning impulses should also be further researched. Moreover, studies on the long-term performance of paper insulation with vegetable oils must be carried out. Considerable efforts regarding the study of paper/vegetable oil insulation have already been undertaken [83, 84]. Detailed reports on pre-breakdown and breakdown phenomena regarding the vegetable oils must also be produced, as was the case in more conventional fluids [12, 85-88]. In conjunction to pre-breakdown and breakdown phenomena and related mechanisms, vegetable oil-based nanofluids must be investigated regarding their dielectric strength, volume resistivity, and dissipation factor [89]. Furthermore, techniques that proved to be useful in studying PD in transformer oil, should be tried and further developed also with vegetable liquids [90-92]. Last but not least, experimental work on blends of mineral and synthetic and natural ester oils should continue, especially in the view of the recent research, which pointed out that the oxidation rate of such a blend was lower than the one of mineral oil [93, 94].

VII. CONCLUSIONS

This – by no means exhaustive – review points the fact that there may be alternatives to mineral oil. Possible candidates for the replacement of mineral oil already exist. A lot of experimental data point out that vegetable oils show specific advantages in comparison to mineral oil, such as biodegradability, flash and fire points, higher permittivity (which is advantageous when the oil is combined with paper insulation), and, on certain occasions, satisfactory dielectric strength. Some negative aspects of the said oils are also mentioned in this short review as well as some still conflicting evidence regarding certain experimental results. Although

vegetable oils seem to be promising candidates as replacements of transformer oil, further experimental work must be done. Thoughts for further research are also given.

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