Mugla Journal of Science and Technology

APPLICATIONS OF NATURAL ESTERS ALTERNATIVE TO MINERAL OILS IN POWER TRANSFORMERS

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Received: 07.09.2023, Accepted: 07.02.2024 Review Article
*Corresponding author DOI: 10.22531/muglajsci.1356778

Abstract

The electrical and environmental disadvantages of mineral oils, traditionally used as insulating fluids in power systems, lead to the search for alternatives. Natural esters produced from vegetable seeds are one of the most important alternatives. Natural esters with high dielectric strength can meet ultra-high voltage transformer design requirements. In addition, they can respond to environmental concerns caused by transformer oils with their biodegradability. This study first compares natural esters with other trans-former oils and explains why natural esters stand out. The basic properties of natural esters are defined in terms of advantages and disadvantages, and power system applications are exemplified. Esterification and synthesis of nanoparticle-added nanofluids, widely used in the literature to improve natural esters' electrical and thermal properties, are presented with experimental applications. Natural esters can have a better oxidation stability with the esterification process. The AC, DC, and lightning impulse (LI) break-down voltages of nanofluids based on natural esters also enhanced by 10% on average. This substation and experimental applications in which natural esters are used show that these environmentally friendly oils can provide insulation requirements in many power system equipment, especially transformers.

Keywords: Transformer Oils, Power Transformers, Liquid Dielectrics

GÜÇ TRANSFORMATÖRLERİNDE MİNERAL YAĞLARA ALTERNATİF DOĞAL ESTERLERİN UYGULAMALARI

Özet

Geleneksel olarak güç sistemlerinde yalıtım sıvısı olarak kullanılan mineral yağların elektriksel ve çevresel dezavantajları alternatif arayışlara neden olmaktadır. Bitkisel tohumlarından üretilen doğal esterler bu mineral yağlara en önemli alternatiflerden biridir. Yüksek dielektrik dayanıma sahip doğal esterler, ultra yüksek gerilim transformatörü tasarımının gereksinimlerini karşılayabilmektedir. Ayrıca doğada çözünebilirliği sayesinde transformatör yağlarının neden olduğu çevresel kaygılara da cevap verebilmektedirler. Bu çalışma öncelikle doğal esterleri diğer transformatör yağlarıyla karşılaştırmakta ve doğal esterlerin sıvı yalıtkanlar arasında öne çıkma nedenlerini açıklamaktadır. Doğal esterlerin temel özellikleri avantaj ve dezavantajları açısından tanımlanmakta ve güç sistemi uygulamaları örnekleri sunulmaktadır. Doğal esterlerin elektriksel ve termal özelliklerinin iyileştirilmesi amacıyla literatürde yaygın olarak kullanılan nano-parçacık katkılı nano-akışkanların esterleştirilmesi ve sentezi deneysel uygulamalarla sunulmaktadır. Doğal esterler, esterleştirme işlemiyle daha iyi bir oksidasyon kararlılığına sahip olabilmektedir. Doğal esterlerle üretilen nano-akışkanların AC, DC ve yıldırım darbesi (LI) delinme gerilimleri de ortalama %10 artmaktadır. Doğal esterlerin kullanıldığı bu şalt sahası ve deneysel uygulamalar, çevre dostu bu yağların, başta transformatörler olmak üzere birçok güç sistemi ekipmanında yalıtım ihtiyacını karşılayabildiğini göstermektedir.

Anahtar Kelimeler: Transformatör Yağları, Güç Transformatörleri, Sıvı Yalıtkanlar

Cite

Duzkaya, H., (2024). "Applications of Natural Esters Alternative to Mineral Oils in Power Transformers", Mugla Journal of Science and Technology, 10(1), 8-16.

1. Introduction

The energy production, transmission, and distribution sector maintains its critical importance in the development of modern societies. The main criteria guiding the energy sector are protecting the environment and developing technologies to meet the increasing demand.

Studies aiming to develop new materials in compliance with environmental criteria defined as a demand/requirement with national and international policies have been going on for more than 30 years in the energy sector [1]. These studies include liquid and gas insulating materials commonly used in power system industry equipment [2-3]. In these studies, using biodegradable oils in the liquid insulating industry is an emerging trend [4]. Another feature of environmentally friendly fluids is low toxicity [5].

The growth of the global population and cities also significantly increases energy demand. The transmission voltage should be increased between the energy generation and consumption destinations to meet this demand. In 2017, ±1000 kV ultra-high voltage (UHV) substation was put into operation in Tianjin, China. At the end of 2017, a ±1100 kV high-voltage direct-current transformer was developed commercially by Siemens and successfully passed type tests [6]. UHV-DC substations are gaining increasing attention as they reduce losses in energy transmission [5]. These examples show that UHV levels are becoming more common in energy transmission. It is inevitable to use new materials and technologies to design power system equipment and transformers that can be used at higher voltages.

Power transformers are this power trans-mission network's most essential and expensive equipment. The reliable operation of these transformers requires a compatible insulation system. Almost one-third of the faults in power transformers are caused by insulating material [7]. These failures reduce the expected life of 35-40 years of high voltage transformers by almost half [5].

Transformers using liquid insulators perform much better than dry-type transformers in overload ability, surge protection, efficiency, space savings, noise, diagnostic capacity, temperature, and expected life [8]. In almost all power transformers, liquid (insulating oil) and solid (cellulose) insulators meet this insulation system. The main functions of liquid insulators are cooling, electrical insulation, protection of solid insulators against air and moisture, corrosion protection, and improvement of the dielectric strength of solid insulators [9]. In addition to increasing the reliability of these transformers, decreasing the cost is among the priorities of manufacturers and consumers. Reducing the size of the transformer or expanding the life cycle is the prominent option to mitigate this cost [10]. For the design of a smaller size transformer with the same power, an insulating liquid with higher dielectric strength and heat transfer capacity should be used [11]. Ideal trans-former oils should have a high thermal conductivity that can dissipate the heat generated in transformer windings and low viscosity for high fluidity at low temperatures [5].

These environmental limitations and increasing energy demand also increase the studies on transformers and transformer oils. Depending on the parameters detailed in this section, it becomes necessary to use alternatives to mineral oils in power system equipment and power transformers. Among these alternatives, interest in insulating natural esters is increasing due to their biodegradability, availability, sustainability, and relatively low cost. The prominent ones in the literature of natural esters are obtained by synthesizing plant sources such as canola, corn, cottonseed, jatropha curcas, peanut, olive, safflower, soybean, and sunflower [12-13].

This study first explains the reasons for using natural esters in the insulating fluid industry by defining the main characteristics of other alternatives in the second section. The main properties of natural esters are represented by their advantages and disadvantages, and the applications of natural esters in power systems, especially in power transformers, are exemplified in the third section. Studies on improving the electrical and thermal properties of natural esters with nanoparticles are explained in the fourth section with scientific research. The discussion section summarizes natural esters' practical and theoretical applications and offers recommendations for further research.

2. Main Properties of Transformer Oils

Transformer oils were first used as an insulating fluid in 1892. These petroleum-based oils are defined as mineral oils in this study. Commercial production of paraffinic-based mineral oils started in 1899 [14]. However, paraffinic-based mineral oils have significant disadvantages, such as high wax content, high pour point, and low viscosity and heat transfer capacity [15]. Although naphthenic-based mineral oils were used to overcome these problems, the high flammability of these oils also revealed safety problems. In the 1930s, less flammable polychlorinated biphenyl (PCB) was used as an alternative until the early 1970s. After the prohibition of the use of this liquid due to the environmental damage of PCBs, the power system industry has focused on alternatives such as synthetic esters (SEs), natural esters (NEs), silicone fluids as well as naphthenic-based mineral oils [14].

Alternatives to mineral oils are evaluated with the characteristics of oils, such as fire safety, increased demand compliance, improved material sustainability, environmental friendliness, extended service lifetime, cost, and availability. When evaluating these characteristics, many parameters, such as high flash and fire points, low pour points, high thermal conductivity, low viscosity, low volatility, high impulse strength, high dielectric strength, and high volume resistivity are analyzed [14].

Mineral oils are the most widely used today due to their low cost, acceptable insulation properties, compatibility with cellulose paper, low pour point, and low viscosity [6]. These are used in all liquid-filled equipment in the power system industry, such as all kinds of transformers (power, distribution, instrument, traction, etc.), bushings, tap changers, terminal boxes, circuit breakers, capacitors, and cables [6, 15]. Extruded insulated cables and binary or ternary SF_6 mixture circuit breakers are used more widely today than oil-filled applications in insulated cables and circuit breakers [15-16].

Despite these advantages and widespread use of mineral oils, they also have significant disadvantages, such as low biodegradability, low fire and flash temperatures, low moisture tolerance, and corrosive sulfur compounds. Mineral oils have a biodegradability below 30% within 28 days [17]. Mineral oil leaks or spills after an accident in trans-formers pollute the soil and groundwater for a long time and threatens human and ecosystems [18]. Burning mineral oils at relatively low temperatures makes fire protection measures such as fire safety, firewalls, and deluge systems mandatory in transformers [8]. In addition, it is estimated that oil resources will run out from the middle of this century [19]. This situation causes a problem with the sustainability of mineral oils in a several billion-liter insulating liquid market.

Since the beginning of the 1900s, alternative liquid insulators have been used to meet environmental, technological, and economic requirements and can mainly be classified into three categories. These

Table 1. Main properties of insulating fluids (updated version of a table in [15]).

Category	**Sub-category**	**Type of liquid**	**Applications**	**Particular properties**	
				Advantages	**Disadvantages**
Mineral Oils	---	Naphthenic, paraffinic	Power, distribution, traction, instrument, and special transformers, reactors, bushings, tap changers, terminal boxes, circuit breakers, capacitors, cables	Viscosity index, resistance to oxidation, low pour point	Relatively low fire point, low moisture tolerance, possible sulfur corrosion
High-molecular Weight Hydrocarbons	---	Paraffinic	Distribution transformers, tap changers	High flash points	
Synthetic Liquids	Synthetic hydrocarbons	Polybutenes, alkybenzenes, DIPN, MIPB, alkyldiarylalcanes	Instrument transformers, cables, bushings, capacitors	Low dielectric losses, adjustable viscosity, good absorbing under partial discharge, good lightning impulse breakdown strength	
	Halogenated hydrocarbons	Askarels (PCB), Polychoro-diphenyl methanes, Polychoro-alcanes	Transformers, capacitors	Nonflammable, thermal stability, biodegradable (except PCB)	
	Silicon oils	Poly-dimethyl siloxanes or PDMS, poly-methylphenyl siloxanes	Traction and distribution transformers, tap changers	Viscosity index, high flash point, gas absorbing under partial discharge, high oxidation stability	Low biodegradability
	Organic esters	Simple esters, phtalates, complex esters, tetraester of pentaerythritol	Traction and distribution transformers, capacitors, tap changers, loading resistance, PCB substitute	High flash point, high moisture tolerance, readily biodegradable (only complex esters), high oxidation stability	
Natural Esters (Vegetable Oils)	---	Castor, coconut, cotton, palm, rapeseed, soybean, etc.	Distribution transformers, capacitors	Low dielectric losses at frequency higher than 1 kHz, nontoxic, readily biodegradable, low inflammable, high breakdown voltage	Low oxidation stability, high pour point, high viscosity
Other Liquids	---	Ethers (alkyl-diphenyl ether, ditolyl-ether)	Capacitors	Relative permittivity, higher than 3 at 20 °C, adaptability	
	---	Nanofluids	Distribution transformers	Adaptability	
	---	Mixed liquids	Distribution transformers, capacitors, cables	Adaptability	
	---	Cryogenic dielectric liquid (nitrogen)	Bushings, superconductivity and cryogenic applications	Reduction or suppression of Joule heating	

categories are mineral, synthetic, and vegetable (natural) insulating oils [14]. Fofana [15] divided them into five categories with a more detailed classification of these oils. The type of liquid, applications, and particular properties of these oils in different categories are given in Table 1 [7, 14-15].

Synthetic insulating liquids can be examined in many sub-categories, as seen in Table 1. Since synthetic oils are four to eight times more expensive than mineral oils, they are used in applications where special features such as fire resistance, partial discharge resistance, and gas absorption ability are desired [10, 15]. Other advantages of these oils are their relatively high biodegradability, high oxidation resistance, less flammability, and more moisture absorption capability without degradation insulation performance.

Ethers (alkyldiphenyl ether, ditolylether), nanofluids, mixed liquids, and cryogenic dielectric fluid (nitrogen) stand out among other fluids used as insulators in power system equipment. These fluids can be used in distribution transformers, capacitors, cables, bushings, or superconductivity and cryogenic applications with special requirements.

3. Natural Esters (NEs) and Their Applications in Power Systems

This section focuses on natural esters, an essential mineral and synthetic oils alternative. NEs, prominent for their biodegradability, have been an important study topic in the insulating fluid literature since the 1990s. The main advantages of NEs over mineral oils are high biodegradability, non-toxicity, high flash and fire points, higher heat transfer capacity, low volatility, high dielectric strength, and high moisture tolerance. The biodegradability of these natural and reproducible oils can be up to 97% in the 21-day [20].

Flash and fire points of NEs are generally over 300 °C. These values are almost twice that of mineral oils. Natural fluids maintain this advantage perfectly for ten years [8]. This low flammability increases the safety level of the power grid and, therefore, the preference for public areas. This high thermal resistance eliminates the need for firewalls and deluge systems traditionally used in high-voltage equipment [8].

The thermal conductivity of NEs is also higher than that of mineral oils [21]. This feature reduces the temperature difference between oil and solid insulators and improves heat transfer. Increased heat transfer enables smaller-size transformer designs with the same power. The dielectric strength of NEs is generally higher than that of mineral oils, which improves the high-voltage equipment's insulating life [13].

Mineral oils are susceptible to moisture. The breakdown voltages of mineral oils rapidly deteriorate in moisture amounts exceeding 30 ppm. NEs have a high moisture tolerance. The breakdown voltage decreases when moisture content exceeds 320 ppm [16]. This feature also contributes to the reduction of moisture in insulation cellulose paper in trans-formers and the more prolonged lifetime of this equipment [18].

Natural esters have been used instead of mineral oils in power system equipment such as small power and distribution transformers, oil-filled cables, and capacitors since the early 1990s [20]. The reliable long-term performance of biodegradable alternative insulating liquids is critical in oil-filled equipment. Fofana et al. [22] examined the mixture of NEs with mineral oils in different proportions regarding electrical and physicochemical properties. It was observed in this study that the relevant parameters were better than traditional mineral oils, while the natural ester content in the mixture was below 20% [22].

Industrial energy sector stakeholders and the literature use NEs in power transformer applications. AREVA Company has developed hermetically sealed power transformers equipped with on-load tap-changers and filled with Envirotemp FR3 natural ester [21]. The designed transformers have the characteristics of 40-31.5 MVA/110 kV and 90 MVA/132 kV, respectively. It is observed that NEs are successfully applied in re-filled and newly designed power transformers in applications in Texas and Memphis, USA [8].

In comparative tests carried out by connecting distribution transformers with 20 kV rated voltage and 50 kVA rated power in parallel, it has been determined that natural ester-based oils are successful in time-based tests for distribution transformers in terms of dielectric and thermal properties [23]. In the tests carried out by Hernandez-Herrera et al. [24] on forty-four distribution transformers with rated powers between 25-75 kVA in different regions of Colombia, it was observed that the thermal characteristics of the transformers using natural esters were better than mineral oils, considering the temperature. Carvalhosa et al. [25] stated that in transformers with 15 MVA rated power, natural ester's dielectric and thermal properties are better than conventional mineral esters, except for impact voltage resistance, and these advantages enable more compact transformer designs.

Alternatives to mineral oils in transformers are mainly evaluated with parameters such as density, viscosity, thermal conductivity, pour and fire point, breakdown voltage, and dielectric constant. Density, viscosity and thermal conductivity, which determine the thermal properties of liquid insulators, are 0.83-0.89 kg/m3 and 0.87-0.92 kg/m3, 3.0-16.0 cSt and 16.0-50.0 cSt, 0.135 W/mK and 0.170 W/mK in mineral oils and natural esters, respectively [26]. Pour point, which is an essential parameter in the use of liquid dielectrics in cold-climate conditions, varies between -30 °C and -63 °C in mineral oils and -10 °C and -33 °C in natural esters [26-27]. The fire point determining fire safety is below 185 °C in mineral oils and above 300 °C in natural esters [27]. Regarding electrical properties, mineral oil and natural esters' breakdown voltage and dielectric constant are 45-55 kV and 60-85 kV, 2.1-2.5 at 25 °C and 2.9-3.2 at 25 °C, respectively [27-28].

The main disadvantages of NEs are high viscosity, high pour point, poor oxidation stability, and poor dissipation factor [15, 29]. One of the prominent methods to overcome these thermal disadvantages and to improve the electrical breakdown characteristics of natural esters is the preparation of natural ester-based nanofluids with different types and concentrations of nanoparticles.

4. Natural Esters Based Nanofluids

A new class of insulating fluids having good heat transfer (cooling) and high dielectric strength appeared about thirty years ago; these are nanofluids [30]. This pioneering study using copper-based nanoparticles to increase the thermal conductivity of industrial heat transfer fluids has defined a new class in fluid engineering. The selection of nanoparticles with high thermal conductivity increases the thermal conductivity of the liquid. For example, some nanoparticles based on copper, silica, and alumina improve thermal conductivity in a linear relationship with the mass fraction in the mixture [5]. Besides the ratio of nanoparticles in the mixture, particle size and shape also clearly affect thermal and electrical properties [31].

Improving the base fluid's thermal and electrical properties with nanoparticles turns nanofluids into an important insulator alternative in oil-filled applications, especially high-voltage power transformers [29]. For example, the top-oil and hot spot temperatures of mineral oil-based nanofluid are reduced by about 5 °C compared with insulating oils. This result is explained by the increase in the thermal conductivity of the nanofluid through the free convection mechanism.

The selection of nanoparticles used to improve the dielectric properties of the nanofluid is quite complex and challenging. At this stage, the choice is made according to the characteristic properties of the nanoparticle, such as the conductivity and the dielectric constant. These particles are widely classified in the literature as conductors, semiconductors, and insulators according to their conductivity. The most commonly used nano-additives are different types of metal and metal oxides [15]. Nanoparticles increase the interaction surface during the movement of charged particles in the fluid and improve the dielectric performance of the nanofluid.

Huang et al. [32] determine that the most frequently used nanoparticles in nanofluids are TiO_2, Fe_3O_4, SiO_2, Al_2O_3, ZnO, and others, respectively, through a detailed literature overview. Others include alternative nanoparticles such as CuO, ZrO_2, and C_{60}, which also increase the dielectric strength of the oils.

Although the AC, DC, positive, and negative LI breakdown voltages of mineral oil-based nanofluids have been studied in detail in the literature, the investigations on natural ester-based nanofluids include entirely new research topics. The enhancement rate of natural ester-based nanofluids in breakdown voltages according to fluid type, BDV type, measurement standard, type, size, and nanoparticle concentrate are in Table 2.

These results are strongly influenced by many parameters such as base fluid, nanoparticle type, size and concentration, manufacturing method, and type of breakdown [40]. Therefore, it is necessary to carry out more tests involving different samples to understand the breakdown voltage characteristics of nanofluids.

Natural ester based nanofluids generally have better partial discharge, AC, and impulse breakdown performance. Therefore, it enables HVAC and HVDC applications to operate at higher voltage levels. These nanofluids are more moisture-resistant; this feature

Table 2. Breakdown voltages enhancement of natural ester-based nanofluids reported in literature.

Ref.	Fluid	BDV Type	Std.	Nanoparticle	Avg. particle size (nm)	Concentration	Enhancement (%)
[33]	RDB	AC	IEC 60156	Fe_3O_4	30		20
		(+) LI	IEC 60897				37
		(-) LI					17
[34]		AC	IEC 60156	BN	50	0.5 g/L	30-33
[35]	FR3	AC	IEC 60156	h-BN	1-2 10^3	0.1 vol.%	18
		DC					19
		(+) LI	IEC 60897				23
		(-) LI					10
[1]	Midel 1204	AC	IEC 60156	Fe_3O_4	50	0.4 g/L	7.07
				Al_2O_3	13	0.05 g/L	7.56
				Al_2O_3	50	0.3 g/L	6.15
				SiO_2	50	0.3 g/L	5.76
[36]	Midel 1204	DC	IEC 60156	Fe_3O_4	50	0.2 g/L	10.56
				Al_2O_3	13	0.3 g/L	7.63
				Al_2O_3	50	0.05 g/L	17.20
				SiO_2	50	0.2 g/L	-4.89
[37]	Midel 1204	(-) LI	IEC 60006	Fe_3O_4	50	0.2 g/L	7.51
				Al_2O_3	10-20	0.05 g/L	16.76
				SiO_2	50	0.2 g/L	13.10
[38]	Midel 1204	AC	IEC 60156	ZnO	25	0.2 g/L	5.8
[39]	Midel 1204	AC	IEC 60156	C_{60}	21	0.4 g/L	7.8
		LI	IEC 60897			0.1 g/L	8.2

improves the reliability of the application [5]. Through these features, natural ester based nanofluids offer opportunities such as designing lighter and smaller size transformers, high voltage transmission capacity, and more reliable and extended life. Despite these better thermal and electrical properties of natural ester-based nanofluids also have critical, controversial challenges such as cost, biodegradability, long-term stability, and compatibility with other elements of transformers.

The cost of natural ester-based nanofluids is higher than conventionally used mineral oils due to the more expensive base fluid and the cost of nanofluid production. However, the two-step procedure is cheaper than the one-step procedure in insulating nanofluid production, and highly advanced and sophisticated equipment is needed for its industrial-scale production [41]. Despite these costs required for the production of nanofluids, the breakdown voltages and fire/flash points of natural ester-based nanofluids, which are almost twice that of mineral oils, allow the design of more compact and safe equipment [38, 42].

The biodegradability of natural ester-based nanofluids varies depending on the nanoparticle's properties and base fluid. It is observed that the environmental effects of these nanofluids are significantly affected by the type of nanoparticle, its concentration, and the production method of the nanofluid [43]. The possible environmental effects of nanofluids recommended for power system equipment should be examined in more detail [44]. Increasing the literature on these nanofluids' life-cycle and end-of-life recycling/recovery is an essential challenge for power equipment using nanofluids [45].

One of the most important disadvantages of nanofluids is long-term stability. The nanoparticles in the nanofluid come together by moving in the direction of the Van der Waals attractive force and causing local aggregation. These agglomerations disrupt the homogeneity of the nanofluid over time. To overcome this long-term stability problem, surfactant chemicals are generally used to reduce the surface tension of the fluid [38]. Surfactant provides better adhesion of nanoparticles to the liquid and causes a repulsive force against the Van der Waals attractive force between nanoparticle molecules [46]. Oleic acid is the most widely used surfactant in insulating insulator-based nanofluids [41, 47]. Since natural esters are obtained from vegetable seeds, the long-term stability of natural ester-based nanofluids with high oleic acid components is expected to be better than mineral oil-based nanofluids.

The main disadvantages of mineral oils commonly used in power transformers are low moisture tolerance and corrosive sulfur decomposition products [22]. These mechanisms damage solid components such as oil-impregnated cellulose paper and gaskets in transformers [22]. The better moisture-holding capacity of natural esters and natural ester-based nanofluids than mineral oils slows cellulose paper aging and can extend transformer life [18, 46].

5. Discussions

Mineral oils, which have been traditionally used in power transformers since the end of the 19th century, have been at the center of discussion for more than 30 years in the search for alternative insulating fluids due to their relatively low dielectric strength and non-biodegradability [1, 15]. During these discussions, synthetic and natural esters come to the fore as alternatives to mineral oils. Although synthetic esters can be preferred in particular applications, there are doubts about their sustainable ability to meet the needs of the billion-liter transformer oil industry due to their relatively high cost and being a by-product of crude oil [10, 15]. Since natural esters can be obtained from plant seeds that adapt to different geographies and can be produced by local farmers, the natural ester alternative has more significant potential than others [12, 13].

Natural esters' AC and positive Lightning Impulse (LI) breakdown voltages are higher than mineral oils [13, 38]. This increase in positive LI breakdown voltages of natural esters compared to mineral oils is between 6.9% and 32.6% in the literature [13, 48]. Negative LI breakdown voltages are close to each other. Natural esters' negative LI inception and breakdown voltages can be reduced by 1.2% to 6.25% compared to mineral oils [49, 50]. This phenomenon is more predominant in electrode arrangements that cause nonlinear electric fields [50]. This increase in AC and positive LI breakdown voltage increases the insulation life of transformers in which natural esters are used. Another advantage of natural esters is that they are almost entirely biodegradable. Natural esters' fire and flash points are almost twice that of mineral oils. The ability of natural esters to withstand high temperatures offers advantageous opportunities in terms of power transformer design and fire prevention systems [8].

Due to these fundamental advantages, natural esters are used in transformer designs and become an alternative in retrofilling applications where mineral oils are changed [21]. In addition, examining the electrical and thermal properties of binary mixtures of natural esters and mineral oil/synthetic esters is one of the essential study topics in the literature [17, 22].

Although natural esters have these advantages, they also have disadvantages, such as high viscosity, high pour point, poor oxidation stability, and poor dissipation factor [15, 51]. These disadvantages of natural esters are the most critical obstacle to their widespread use and must be minimized. It is recommended to convert unsaturated fatty acids to saturated fatty acids by the esterification mechanism to increase oxidation stability [13].

Another method used to increase the electrical and thermal characteristics of natural esters is natural ester-based nanofluids, which form with nanoparticles of different sizes and concentrations [31]. Investigation of thermal and electrical characteristics of nanofluids created with other nanoparticles is an important research topic.

6. Conclusions

Insulating fluids are widely used in the power system industry in many equipment such as power, distribution, traction, instruments, special transformers, reactors, bushings, tap changers, terminal boxes, circuit breakers, capacitors, and cables. These fluids are also defined as transformer oil because they provide insulation with cellulose (solid) material in almost all transformers except for gas-insulated system (GIS) transformers. This transformer oil market is several billion liters [15].

Mineral oil varieties have dominated the transformer oil industry since the beginning of the previous century [14]. Despite the advantages of mineral oils, such as low cost, low pour point, and viscosity, there are many disadvantages, such as low biodegradability, low shrinkage and flash points, low moisture tolerance, and corrosive sulfur compounds [6, 19]. In addition to these disadvantages, the fact that mineral oils are a by-product of crude oil and the shrinking petroleum industry market accelerates the search for alternatives. Although many insulating fluids are described in Table 1 among these alternatives, the prominent ones are synthetic and natural esters. Synthetic esters are a by-product of crude oil synthesized by a process similar to mineral oils. This situation makes synthetic esters controversial to meet the demand of the global transformer oil industry, except for special applications. Besides, since the cost of synthetic esters is 4-8 times higher than mineral oils [10], a more economical alternative must be found in the transformer oil industry of several billion liters.

Natural esters have been studied in the transformer oil industry as an alternative to mineral oils for over 30 years. Neutral esters are obtained by different extraction processes from vegetable seeds such as canola, corn, cottonseed, jatropha curcas, peanut, olive, safflower, soybean, and sunflower [12, 13]. These natural esters can be highly diversified depending on the vegetation geographies of the plants. In addition to this richness of resources, natural esters are an advantageous alternative in high-power hermetically sealed transformer designs with their better breakdown voltage performance, fire/flash points, and biodegradability compared to mineral oils.

Natural esters also have disadvantages, such as high viscosity, high pour point, and poor oxidation stability. Esterification reactions are recommended to increase oxidation stability among these disadvantages [13]. The second method to improve natural esters' thermal and electrical properties is using nanoparticles. Depending on these parameters, homogeneous nanofluids obtained by adding nanoparticles of different sizes, conductivity, and densities indicate better AC, DC, and LI breakdown performances. Examining the thermal and electrical properties of these nanofluid applications using other nanoparticles can allow the design of higher power and environmentally friendly transformers.

Using natural esters can reduce environmental concerns that are increasing daily on a global scale. In addition, the ability to produce different natural esters in different bio geographies offers the opportunity to improve reliability and sustainability in the transformer oil industry.

7. Acknowledgment

This work is supported by the Scientific and Technological Research Council of Turkey's (TUBITAK) 2219 grant program.

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