Transformer Design and Manufacturing for Natural Ester Fluids

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Introduction:

One of the most important and expensive equipment in Transmission and Distribution network is the transformer. The main function of the transformer is to transform the energy power at the voltage which is best for the economy and thus sound electrical and thermal design of transformer is paramount importance. Transformers are filled with fluids for dielectric and thermal purposes. Petroleum based mineral oil used as a fluid to fulfill the dielectric and thermal requirement for over 100 years. Mineral oil is not a biodegradable fluid and this led to the developments of environmentally friendly ester insulating liquid for electrical power applications. The high fire point of ester oil reduces risk for transformers installed in or close to a building or people. This is biodegradable and fire-resistant fluid however has high viscosity than mineral oil.

VTC/GTC team has successfully designed and tested a 150 MVA transformer insulated with natural ester FR3 fluid. Our team has built and tested units up to 750kVp Basic Insulation Level.

Properties of Natural Esters:

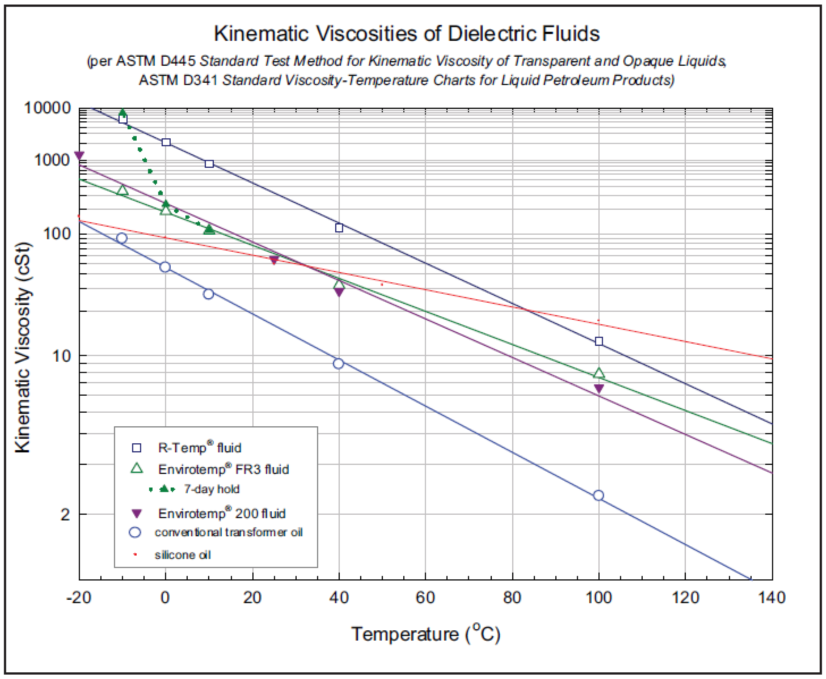


Figure1. Viscosity of different fluids

Virginia Transformer builds Envirotemp® FR3™ ester filled transformers for bio-degradable application and indoor application based on customer requirements. Ester FR3 is fire resistant fluid developed from edible seed oil and food grade performance enhancing additives. It does not contain any petroleum, halogens, and silicones. It is tinted green in color and has fire point of 360°C and flash point of 330°C. Natural esters can hold higher amount of water than mineral oil. Due to this property, water content in newly received oil can be 50 mg/kg as per IEEE. Also, the power factor of 1% in ester is equivalent to 0.5% in mineral oil. Viscosity of fluid is 4 times that of mineral oil for the operating temperature of 80°C shown in figure1.

Design:

Design of transformer using natural ester requires fundamental understanding of the fluid electrical and thermal properties. Electrical properties such as breakdown strength of the liquid under power frequency and lightning impulse condition plays a big role in electrical design of the transformer. Main properties which govern the design are tabulated below.

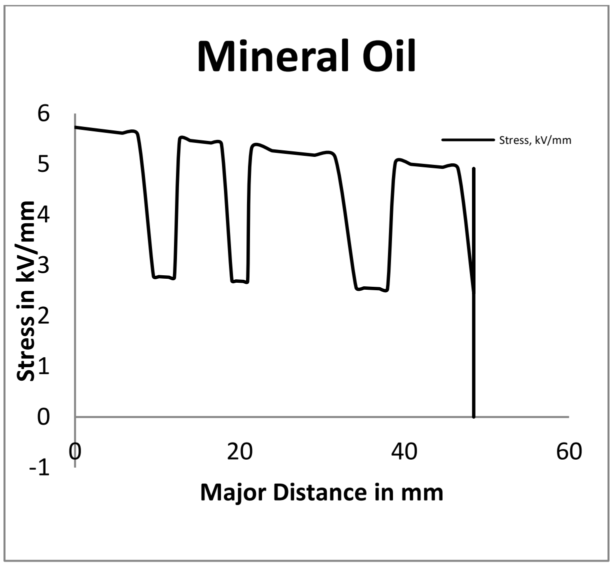
Table1. Comparison of properties

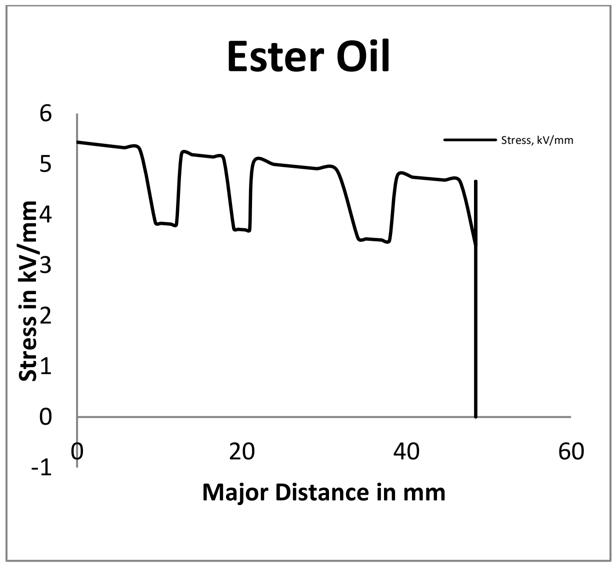
Material	Property	Mineral oil	Natural Ester
Oil	Dielectric constant	2.2	3.2
	Viscosity	3.5 cSt	12 cSt
Paper	Dielectric constant	3.2	3.4
Low density pressboard	Dielectric constant	4.4	4.6
High density pressboard	Dielectric constant	4.4	4.6
Molded Pressboard	Dielectric constant	3.5	4

Electrical design:

Dielectric performance of ester fluid is different than what is understood for the mineral oil fluids. Based on the literatures available in IEEE or other technical forum indicates that ester fluid performance is poorer for the field around sharp electrodes. Transformer has many surfaces/edges which are not perfectly smooth and can cause fields to rise up and go beyond the limit. Traditionally transformers are designed with stress limited in the oil duct around electrodes as oil carries the high stresses. Weidmann has published the partial discharge inception limit of oil ducts for different configurations for mineral oil years back and this has been followed by the industry around the world.

There is no such partial discharge inceptions curves are available for the ester fluid due to the erratic nature of the fluid. Design and process should work together for the transformer to produce acceptable partial discharge level under ester fluid. Ester fluid behavior under different electrode shapes applicable to transformer has 15 to 30% lower dielectric for impulse withstand. Due to the difference in permittivities, stress in ester fluid is 5 to 7% lower and stress in solid insulation is higher in ester fluid by 37% (approximately) than mineral oil. For a typical gap between the winding, electrical stress distribution is shown below. Low voltage winding corners are secured with additional reinforcements for the protection against corner stresses. Molded insulation parts are used based on the voltage class requirement. The designs are verified by 2D/3D FEM analysis.





Due to stress shift from the liquid to solid insulation, stress in high voltage leads can be challenging for the stress control. Radial insulation on the lead shall be evaluated by the trade-off between electrical and thermal requirement. Comparison of lead stress between mineral oil and FR3 fluid tabulated below.

Table2. Comparison of stresses for high voltage lead

DIL (kVrms)	Mineral Oil (kV/mm)		FR3 (kV/mm)	
	Stress on cable surface	Stress on insulation surface	Stress on cable surface	Stress on insulation surface
220	5.8	4.02	7.87	3.74
260	5.92	4.41	8.07	4.13
300	6.5	4.48	8.81	4.17

Thermal design:

Viscosity of ester fluid is almost 4 times that of the mineral oil for 80°C temperature. The viscosity of the fluid introduces complexity in thermal performance of the transformer even though the paper degradation is not compromised. IEEE limit of hot-spot rise is 80°C for 65°C winding rise transformer. To meet the thermal performance, radiators and fans are selected based on the thermal calculation considering viscosity and test results of the units already build and tested by VTC. Special radiator design is adopted by VTC/GTC for catering the ester fluid requirement. Oil ducts closer to winding are selected judiciously for the oil to flow in the narrow room available close to winding. Duct size cannot be increased beyond certain limit as the dielectric strength reduces.

Manufacturing and Processing:

FR3 fluid received in plant is tested for dielectric breakdown (BDV) as per IEEE Std C57.147. Dedicated storage tanks cleaned every time new oil filled are maintained in all facilities to keep it free from residual fluids and moisture. Storage tanks are kept under positive pressure of nitrogen. FR3 fluid is stored indoor and dedicated oil hoses and pumps are used. Separate in-house processes are maintained for the oil received in totes and in tankers.

Approximately 40°C temperature difference brings the viscosity close to mineral oil for the natural ester. Oil filling is done under the temperature of 60°- 80°C and under vacuum to improve the impregnation process. Settling time after oil filling is doubled compared to the mineral oil for the oil temperatures of 60°- 70°C. Testing of the transformer is done with FR3 fluids and not with mineral oil fluids.

Conclusion:

VTC/GTC understands the properties of ester fluids and has been building transformers with FR3 fluid from early 2000's. We have dedicated equipments in shop for storage and processing requirements, dedicated design and process guidelines for each plant based on the plant capacity to cater the needs of the customers requiring ester fluids.