FR3® fluid behavior in cold temperature environments

Reference Data

R2020

INTRODUCTION

Dielectric liquids perform at least three important tasks in the operation of transformers: acting as an electrical insulating medium, as a coolant to transfer heat from the core and coils to the tank walls and radiators, and as an essential source of information for assessment of overall operation conditions. Transformers require a dielectric liquid to be able to perform these functions even in very cold conditions and Cargill FR3® fluid is able to fulfill all these requirements.

A FR3 fluid filled transformer will not require special procedures for cold start (energization) at low temperature limits when compared to a mineral oil filled transformer, complying integrally with the normal operation conditions described in IEC 60076-2 and IEEE C57.12.00. Any other more restrictive conditions potentially required by transformer accessories should be taken into consideration.

DIELECTRIC ASPECTS

A transformer dielectric liquid must be a good electrical insulator at all usual service conditions. FR3 fluid maintains its dielectric performance down to -50°C (-58°F).

Various factors impact dielectric strength, but typically the most common and important contaminant is water. For all dielectric liquids, the dielectric strength decreases as water content increases proportionally to the relative saturation.

Water in excess of the dielectric fluid's saturation point at a particular temperature, the point where the fluid cannot hold any more water, becomes "free" water. At 25°C (77°F) mineral oil saturates at about 70 mg/kg (ppm) and FR3 fluid at about 1000 mg/kg. However, at -20°C (-4°F), mineral oil saturates at about 8 mg/kg, while FR3 fluid saturates at about 425 mg/kg.

Therefore, FR3 fluid is less likely to reach saturation in cold ambient conditions, preventing the presence of free water and maintaining the dielectric strength during transformer start up.

Figure 1 shows how temperature affects the fluid's saturation point. The hotter a transformer operates, the more moisture migrates from its paper into fluid. The fluid can absorb more moisture driven off the paper due to significant increases in its saturation point as temperature increases. Additionally the hotter a transformer operates, the faster the insulation paper ages, producing more moisture. This water migration continues until both the paper and fluid are at relative saturation equilibrium at the current temperature.

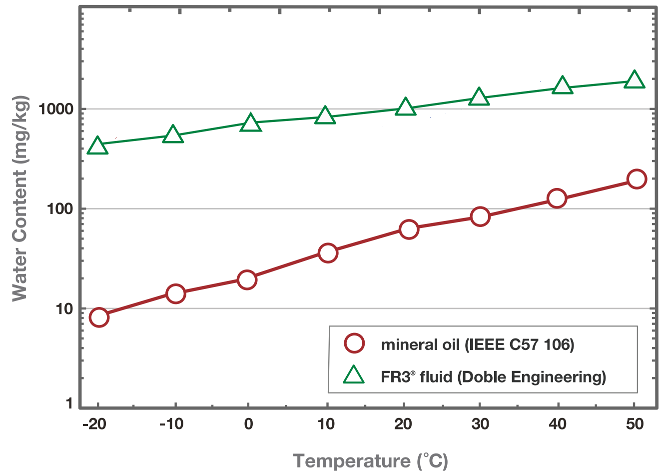

Figure 1
FR3 fluid saturation points

In general, moisture content above 40% of relative saturation is detrimental for the breakdown voltage. Energizing mineral oil filled transformers at temperatures around -20°C (-4°F) would require a moisture content not more than 3 mg/kg, an extremely low level. For FR3 fluid-filled transformers, up to 160 mg/kg would be acceptable.

POUR POINT AND VISCOSITY

Pour point is defined as the lowest temperature at which a fluid is observed to flow under specified conditions (ASTM D97 and ISO 3016 are commonly used test methods). The pour point does not provide information about the undergoing process with the liquid, and can be influenced by the effect of viscosity or previous thermal history of the specimen. Therewith, the pour point may provide a misleading view of the liquid handling properties and demands additional fluidity tests for transformer cold start purposes.

Conventional transformers filled with mineral oil have pour points below -40°C (-40°F), compared to approximately -21°C (-6°F) for FR3 fluid. A viscosity comparison, at low temperature, of FR3 versus synthetic ester reinforces the importance of evaluating additional properties other than pour point to assess the viability of transformer cold start abilities. Figure 2 presents viscosities at many temperatures for FR3 fluid and synthetic ester liquid.

Although synthetic esters reach a pour point as low as -56°C (-68°F), their viscosity is higher than FR3 fluid at any temperature lower than +15°C (59°F). As an example, below -20°C (-4°F) the viscosity of natural ester is 600 cSt compared to the synthetic ester viscosity above 1400 cSt, which significantly reduces the oil flow through windings at the lowest required standard operating temperature per IEC and IEEE.

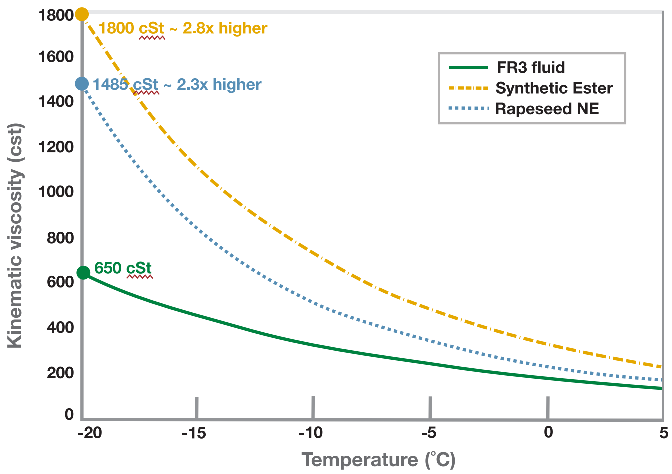

Figure 2
Kinematic viscosity of FR3 fluid, Synthetic ester, Rapeseed NE.

Consequently, when performing cold start operations in a transformer with dielectric fluid at temperatures from 0°C (32°F) to -20°C (-4°F), the conditions to flow the liquid and perform any mechanical movement inside the transformer will be more difficult for synthetic esters than FR3 fluid. Temperatures lower than this are not very frequent.

Additional considerations should be taken for locations where the average ambient temperature may get lower than -21°C (-5°F) for several days in a row. Taking into account the large volume of a dielectric liquid in any transformer, the reduction of flow is a gradual process dependent on the average temperature over a period of time, rather than lowest peak temperature. Typically, even for a small distribution transformer filled with natural ester liquid, it takes more than 3 days of an average temperature lower than pour point to initiate the formation of small crystals.

Figure 3 shows the temperature and time required for FR3 fluid viscosity to change. The named zones "Honey"; "Margarine" and "Ice Cream" are used to make it easier to understand the relative liquidity for each area. The time scale included in the graph is especially important as it indicates that the liquid preserves fluidity during the process, preventing formation of voids and cracks.

In comparison, mineral oil may shrink, crack, and create voids as it cools at its pour point. Energizing a transformer when the dielectric liquid contains voids could create an immediate dielectric weakness and possible failure, in addition to the risk created by the formation of free water.

HEAT TRANSFER

Unlike water, natural ester fluids do not have a well-defined solid/liquid phase transition temperature. During extended exposure to very cold temperatures, natural esters will gradually increase in viscosity, forming small crystals, but still be able to flow and transfer heat.

Figure 3 is based on 55-75 liters (15-20 gallons) of FR3 fluid in a transformer and indicates the time interval required for such a small volume to reach each zone condition. Larger volumes, such as those in a power transformer's main tank, will take longer to reach these states when filled with FR3 fluid. A large power transformer will require several weeks exposed to average ambient temperatures lower than -25°C (-13°F) to reach the "honey" zone. Additionally, the more you move to the center of the fluid volume, where the core and coil are located, the longer it will take to reach such a state. So, the ducts inside the coils would be the least affected region.

Furthermore, a paper presented at IEEE CEIDP [2] summarizes a series of full load cold start tests performed to determine the temperatures of transformer coils when FR3 fluid is below its pour point temperature. Distribution transformers instrumented to measure core, coil, and oil temperatures were energized at full rated load at -30°C (-22°F). The units showed no abnormal temperature excursions and remained below the temperature limits established in IEEE standards.

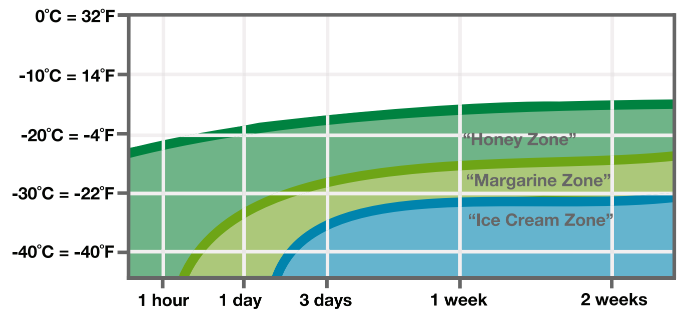

Figure 3
FR3 fluid consistency at low temperature.

Another recent IEEE paper [3] presents a similar study of a 240 MVA GSU transformer, successfully energized during a series of days with temperatures around -20°C (-4°F) near Burlington, Iowa (U.S.).

The hundreds of FR3 fluid filled transformers in operation in Norway and Canada since the early 2000's, supports the applicability of the fluid in such climates.

REFERENCES AND FOOTNOTES

[1] R2120, "Cold Start Recommendations for FR3 Filled Transformers," Cargill Industrial Specialties, Plymouth, MN, 2017.

[2] K.J. Rapp, G.A. Gauger, J. Luksich, "Behavior of Ester Dielectric Fluids Near the Pour Point", IEEE Conference on Electrical Insulation and Dielectric Phenomena, October 17-20, 1999, Austin, TX

[3] S. Moore, W. Wangard, K. J. Rapp e R. D. L. Woods, "Cold Start of a 240-MVA Generator Step-Up Transformer Filled With Natural Ester Fluid," IEEE Transactions On Power Delivery, Vol. 30, No. 1, February 2015.

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