

Distribution Transformers for Improved Reliability and Environmental Safety

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Introduction to Møre Trafo

Møre Trafo AS is located at Aursnes in Sykkylven, Sunnmøre, 30 km from the city Ålesund on the western coast of Norway. Møre Trafo has 120 employees, and annual sales of about 17 million Euros. Møre Trafo makes two main products; transformers and substations. About 2000 oil-filled distribution transformers a year are produced in Sykkylven in sizes from 30 to 3150 kVA. Substations are delivered as outdoor or indoor operated. Customers are mainly Nordic electricity suppliers and private industry.

Liquid Filled Transformers

It's well-known that oil immersed distribution transformers can be built with very low losses compared to dry-type transformers. Oil is a better cooling and insulation medium than air, core-and winding-design can be smaller in oil, therefore have lower material consumption and lower losses.

One goal in our transformer design planning is to take long-term responsibility for our global environment. Other goals are low fire risk and use of non-toxic biodegradable or recyclable materials.

Envirotemp® FR3™ fluid is a natural ester made from edible seed oils and is greater than 99% biodegradable in standard test methods. FR3 fluid was developed by Cooper Power Systems during the nineties and the base fluid is food-grade soybean oil.

Møre Trafo has been marketing Envirotemp FR3 fluid, mainly in the Nordic countries, since early 2000. Large utilities like Hafslund Nett in Oslo have replaced silicone oil with FR3 fluid for transformers in and near buildings in 2004.

Design and Lifecycle Cost

Since 1990 Møre Trafo has developed compact distribution transformers which are 98% recyclable. The vision to be environmentally friendly has directed the removal of plastics and wood from the transformer design.

Two percent of weight of paper insulation can't be recycled, however, paper is still the best high-voltage dielectric in combination with transformer oil. After 30 years of life, the materials in an oil transformer can easily be taken out and recycled at low cost. The core design is steplap, i.e. low noise and low loss, laser-scribed HIB quality. The oval winding design is with copper (Cu) or aluminum (Al).

Aluminum is supplied from Hydro in Karmøy, Norway, at low pollution cost due to green energy production and short transport distance. In spite of 1.6 higher resistance in Al compared to Cu, aluminum is favorable in transformer windings, especially in foil windings, because of low eddie current losses. Generally, the eddie current losses are



PowerSafe Distribution Transformer with short connections inside and low current densities secures good mechanical strength. IEC60076 -5 result is only 0.45% change in reactance after short-circuit test.

inversely proportional with the square of the resistance of the material, i.e.
 $Al \text{ e.c.losses} = 0.4 \times Cu \text{ e.c.losses}$
Additionally, eddy current losses in foil windings appear, depending on geometry, because of the field generated from inlet and outlet currents in buss bars.

Hermetically sealed transformers, completely filled with oil and with insulated bushings, are nearly

maintenance-free and able to survive in corrosive and rough atmospheres. The hermetic compact design with less oil volume makes, together with Envirotemp FR3 fluid, a long-term, cost-effective transformer.

The transformer tank is type-tested for cyclic pressures corresponding to 30 years of life. Typical pressure rise at rated load is 0.2 bar for 30 kVA and 0.05 bar for 3150 kVA. The coefficient of expansion is approximately equal for mineral oil and FR3 fluid; $0.75 \times 10^{-4} / \text{degrees C}$, however, the coefficient for silicone oil is 1.04 and the pressure rise experienced is 20-30% higher.

Ageing and Mechanical Strength

The hermetic design conserves the FR3 fluid and the paper apart from oxygen. The lifetime of the insulation system is then determined by the ageing of the paper insulation.

The ageing of paper is accelerated by increasing the temperature and the amount of humidity in the paper. In new transformers the amount of humidity in the paper should be below 1%, however, when paper deteriorates, water is created.

As the transformer heats up, water moves from the paper into the oil as long as the oil is capable of dissolving more water. FR3 fluid can dissolve a much higher amount of water than mineral oil. This explains why the lifetime of paper immersed in FR3 fluid is five to eight times longer than in mineral oil.

A forced ageing test in a sealed tube at 150° C for 4000 hours shows that the water content of paper increases up to 3.5% in mineral oil, and the tensile strength of the paper is reduced to only 10% of the initial strength. In the same test with FR3 fluid, the paper retains 60% of the tensile strength and the water content of the paper decreases from its initial 0.75% down to 0.1%. The FR3 fluid is drying the paper.

In mineral oil the tensile strength of the paper is decreased to 50% after only 500 hours. If the tensile strength becomes less than 50%, short-circuit forces can be a problem for the transformer. This is caused by fault condition and impulse currents in the power line network.

If the paper tensile strength is below 20%, paper is so brittle that thermal expansion and natural vibration from AC currents in the transformer itself can cause damage.

Electrical Stress and Reliability

Dielectric breakdown in dry and clean oil is about 60-70 kV in both mineral oil and FR3 fluid (IEC60296). The dielectric strength in FR3 fluid is less influenced by water content than mineral oil. The amount of water that can be dissolved is dependent on temperature. With 100 ppm water, the mineral oil dielectric breakdown drops significantly to 10-20 kV. FR3 fluid breakdown stays at a level above 50 kV with 400 ppm water dissolved.

Dielectric breakdown in transformer oil drops significantly with contaminations like dust and particles in combination with water. Therefore, a clean production process is very important, using production methods avoiding loose cellulose fibers, to secure long-term reliability.

Regarding electrical stress, the oil is the weakest point in the insulation system. The electrical stress in the insulation system is inversely proportional to the dielectric constant = ϵ .

ϵ mineral oil = 2.2, ϵ paper = 4.4, supposing the stress in the paper to be 4 kV/mm, the stress in the mineral oil should be $4 \text{ kV/mm} \times 4.4 / 2.2 = 8 \text{ kV/mm}$.

ϵ FR3 fluid = 3.2 and the electrical field distribution is different $4.1 \text{ kV/mm} \times 4.4 / 3.2 = 5.6 \text{ kV/mm}$. The electrical stress is 30% lower in FR3 fluid in comparison to mineral oil.

Temperature Rise and Risk

The lifetime of mineral oil transformers can be 30-50 years, even longer. The reason for this long lifetime is low average loads, at 40-70%. The utilities

wish to load the transformers higher. Unless there is a method for keeping the paper insulation dry, this could result in a higher failure rate.

The excellent properties of FR3 fluid in drying the paper makes it possible to run the transformers at higher loads while preserving their long life.

The lifetime of the paper insulation system can be estimated using



Author's view of Hammarsettindane and Straumshorn – Sykkylven

Montsingers rule and Arrhenius law regarding chemical deterioration. The lifetime is dependent on the average temperature in the hottest spot of the insulation system. In a three-phase transformer this should be in the upper part of the middle leg winding, either the high- or low-voltage.

Measuring the top oil temperature and knowing the temperature rise to hotspot, the lifetime could be estimated. The temperature rise from top oil thermometer to hotspot is dependent on the transformer design. In a small distribution transformer this temperature rise is a lot higher because of many turns and layers in windings, compared to bigger transformers with less turns and more cooling ducts. Temperature rise tests, IEC60076-2, show approximately same results for FR3 fluid as mineral oil. Silicone oil rises 4-5° K more due to higher viscosity.

Fire Protection and Reliability

Mineral oil is a low toxicity fluid and is 25% biodegradable. However, the low fire point, at 150° C, requires additional protection (and costs) for buildings and equipment to reduce fire risk.

In Norway, mineral oil ONAN installations with total power above 1600 kVA requires automatic fire protection or oil containment. According to new regulations, this need is proposed to be above 900 kg of mineral oil. In old 1600 kVA transformers weights up to 1100 kg are not unusual. Today in new ONAN PowerSafe design the oil weight is 695 kg in a 1600 kVA transformer.

Regulations allow KNAN transformers with fire point higher than 300° C to be installed in buildings as dry transformers, however, the oil must be accumulated in case of leakage. This is normally accomplished with a low cost tray or edges around the transformer room.

Installations in tunnels and buildings with silicone oil have provided good reliability for 30 years, however, some problems have been reported with tap changer-spring-contacts, and silicone oil is not biodegradable. FR3 fluid has a very high fire point of 360° C.

Retrofilling

Silicone oil should not be mixed with other types of dielectric fluids. Small contaminations (ppm) can cause oil foaming under vacuum.

FR3 fluid is mixable with mineral oil and synthetic esters, among others. If FR3 fluid contains more than 7% mineral oil the firepoint will drop, however, the excellent properties of FR3 fluid keeping the paper dry for long life will remain at any mixture with mineral oil.

We have found that a cost-effective and low loss distribution network with high reliability can be planned and built using high-voltage cables to the centers of load and placing low loss distribution transformers with biodegradable FR3 fluid in these centers. ■

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