LAUDA TecInfo No. 6

Interfacial instrumentation and viscometers control the ageing of transformers

Transformers (illustration no. 1) are some of the most important elements in the supply of energy. In addition to the main materials of copper, magnetic sheet steel and insulating materials (paper, pressboard, wood), transformer oils are used for insulation and cooling purposes. In normal operation, power and distribution transformers frequently reach an age of over 30 years. Unusual loads such as transient voltages, overheating during normal operation or disruptions to the cooling, however, result in the accelerated ageing of the organic materials and a reduction in the serviceable life (illustration no. 2). Special monitoring methods have been developed for the early detection of accelerated ageing conditions by the Siemens transformer factories and manufacturers. Of central importance here are the interfacial tension and viscosity measurements, which play a significant role in "transformer life management" and in the design and testing of new materials.

Fig. 1: High-performance transformers at the Siemens transformer factory in Nuremberg

Measuring interfacial tension (IT)

The interfacial tension in transformer oils provides information regarding the presence of polar substances which form due to the decomposition of oil and paper. Molecules located directly on the surface of an oil which come into contact with air experience a stronger force in the direction of the liquid than in the gas phase – this is caused by mutual attraction. A similar imbalance also arises on the interface of two non-miscible liquids, e.g. water and oil (illustration no. 3). The liquid is pressed into a shape with as small a surface as possible, i.e. the water forms spherical drops in the oil. The molecules of surfactants, such as those in detergents, generally have a hydrophobic hydrocarbon chain and a hydrophilic "head". These molecules settle in the energetically most favourable position on the surface of the oil/water, hereby reducing the interfacial tension (IT). Since very small concentrations are sufficient to coat the surface, measuring the IT can even detect the smallest provable traces of this group of substances which could otherwise only be proven with a great deal of analytical effort. The unit of measurement for the IT is given in milliNewton/m (mN/m).

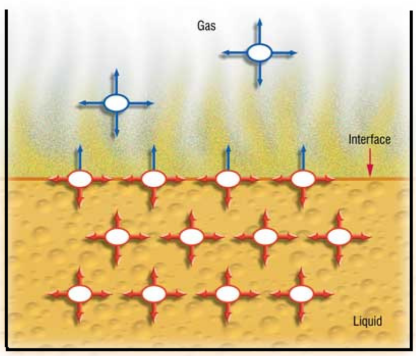

Fig. 2: interface water/air

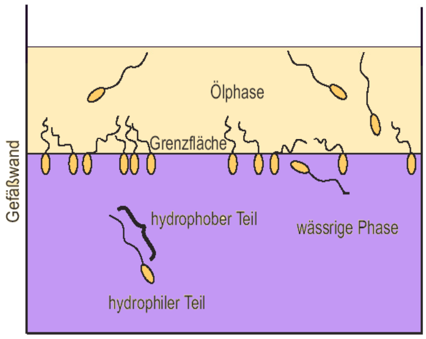

Fig. 3: amphiphilic molecules on the oil/water surface

LAUDA DR. R. WOBSER GMBH & CO. KG • Pfarrstraße 41/43 • 97922 Lauda-Königshofen • Germany
Tel: +49 (0)9343 503-0 • Fax: +49 (0)9343 503-222 • Internet: www.lauda.de • Email: info@lauda.de

There are several different ways of measuring the IT. Using the long-since familiar, tried-and-tested du Noüy method (ASTM D971:99a and ASTMD1331), using an extremely sensitive load cell by means of a horizontal platinum ring, the maximum force - F_{max} - exerted on the surface of the lamella as it is removed from the oil just before it breaks, is measured (illustration no. 4).

Fig. 4: fully-automatic, mobile ring tensiometer according to du Noüy measuring

An alternative method for determining the IT is the drop weight/drop volume method according to ASTM D2285:99. With this method, using a vertically-suspended syringe on a levelly-ground capillary, drops of water are created in the insulating oil to be tested. The volume of the drop created on the end of the capillary is increased by means of pressing down the syringe plunger until the drop comes off and, due to the oil, drops to the bottom of the collecting cuvette: it is during this process that it is detected by a light barrier. From the measured distance of the syringe plunger and the known syringe cross-section, the volume and, hence the IT, of the drop is determined (illustration no. 5). The accuracy of both methods described above is dependent on external influences, such as the homogeneity of the samples and the cleanliness of the transportation and laboratory receptacles and the parts of the equipment which come into contact with the sample.

IT as the index of insulating oils

IEC 60422 forms the foundation for the supervision and maintenance of insulating liquids. In addition to the quantitatively difficult to feel parameters of colour and appearance, the analytically determinable water content, the neutralisation number and the loss factor, the interfacial tension (which is also simple to measure in mobile use) is an indicator of the quality of the transformer oil. This test is a measurement for the concentration of the polar molecules in the oil which come into being during the ageing process. The higher this concentration, the lower the interfacial tension, and the higher the tendency of the insulating oil to form sludge. The cause of this is the advanced ageing (oxidation) of the oil through, for example, penetrating water or the ageing of the cellulose. This process worsens the dielectric properties of the insulating system, especially of solid insulation. Sludge severely impairs the winding cooling, thus preventing the heat removal. This heat accumulation, in turn, makes the winding paper age very fast. Interfacial tensions of less than 15 mN/m indicate the possibility of sludge formation. For this reason, maintenance measures are recommended for values under 22 mN/n, irrespective of the values of the neutralisation number.

Fig. 5: the PC-controlled drop volume tensiometer provides information on the adsorption behaviour of amphiphilic impurities on the surface

Viscometry using the Ubbelohde method

The viscosity of the insulating oil is decisive for the design of the cooling system of a transformer. The lower the viscosity, the better the cooling. IEC 60296 defines a maximum viscosity of 12 mm2/s at 40°C for transformer oils. Indirectly, viscometry also tests the quality of the insulating papers. One distinguishes between the density-dependent viscosity, i.e. dynamic (unit: 1 cp = 1mPas) and the density-independent viscosity (unit: 1 cst = 1mm2/s). The latter can be determined very accurately with glass viscometers, e.g. of the Ubbelohde type, by measuring the time required by a specific amount of sample to pass through a well-defined capillary under the influence of gravity. In modern equipment, light barriers (illustration no. 6) have long since replaced eye and stopwatch. The Ubbelohde viscometry method has long since been tried and tested, and is now available as a highly-automated version. Not only time measurements are made: dosage and cleaning are also carried out. Modular systems are especially suitable for this, since the configuration is precisely cut out to match the requirements of the user and can adapt with the requirements.

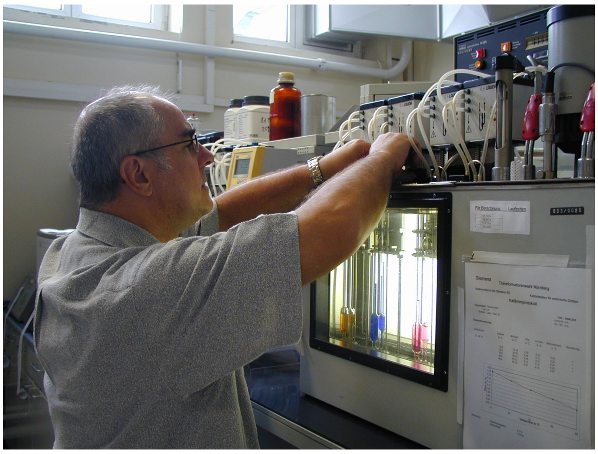

Fig. 6: modern PC-controlled measuring system using the Ubbelohde method for the highly-accurate determination of the viscosity of insulating oils (ochre coloured) and the DP value of insulating papers dissolved in CED (blue)

Determination of the quality of winding papers

Paper is a polymer, i.e. it is made up of long strands of polymerised glucose rings. The degree of polymerisation (DP value) is directly linked to its mechanical strength, the tensile strength. New paper typically has a DP value of between about 1,000 and 1,100, which diminishes over time due to the ageing process.
The DP value of insulating papers is important for the mechanical and, particularly, the short-circuit load of the transformers. A decline of the DP value to around 200-150 signifies the end of the transformer’s life.

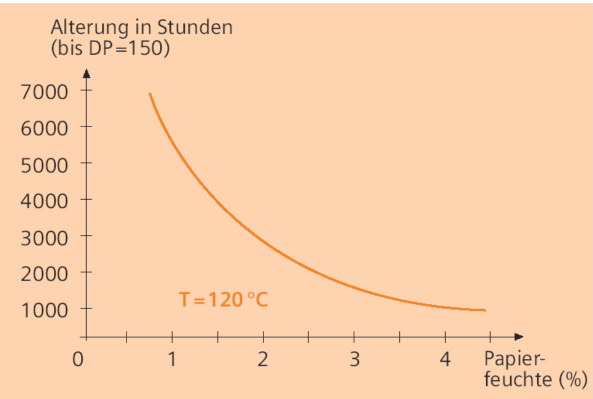

Fig. 7: dependency of paper ageing on the moisture content of the paper (parameter: DP value)

The rate of ageing depends greatly on the temperature and the water content in the insulation (illustration no. 7). Transformers with damp insulation and high operating temperatures can age up to 20 times faster.
The degree of polymerisation of an insulating paper is determined by means of solvent viscosity in accordance with IEC 60450. The solvent viscosity is a tried-and-tested, easily carried out method for determining the strand length change in polymer. The intrinsic viscosity determined from the ratio between the viscosity value of the polymer solution and the solvent and the concentration (the IV value) correlates with the degree of polymerisation (i.e. the strand length). Standards determine which measuring conditions are to be observed. The solvent cupriethylendiamine (CED) is frequently used for paper and cellulose, since it ensures the gentle (i.e. non-destructive) development of the paper molecules in the solvent.

LAUDA DR. R. WOBSER GMBH & CO. KG • Pfarrstraße 41/43 • 97922 Lauda-Königshofen • Germany
Tel: +49 (0)9343 503-0 • Fax: +49 (0)9343 503-222 • Internet: www.lauda.de • Email: info@lauda.de

Resistance test of insulating oils faced with extreme climates

Transformers are frequently used in areas with very severe climatic conditions. In Arctic regions, the temperature in the switched-off transformer can sink to below -40°C which, in addition to a dramatic increase in the viscosity and, hence, to a change in the insulating properties, under certain circumstances can result in damage to the transformer. It is therefore necessary to make-to-measure and test the oils for the potential extreme temperatures. Due to their modularity, the Ubbelohde viscosity measuring systems used for measuring the DP, are ideal. One of the measuring tripods is placed in a cooling thermostat, thus enabling a wide temperature range of below -40°C to well above the operating temperature. Due to the higher viscosity at minus temperatures, the Ubbelohde viscometer must be replaced by one with a greater capillary radius. These measurements can thus be taken parallel to the DP tests with the same device.

Conclusion

Fully-automatic tensiometer and viscosity measuring systems in conjunction with precise thermostating technology increasingly simplify the monitoring of important characteristics of transformer oils and insulating papers. They are essential testing methods as part of “transformer life management” and in the development of new materials.

Authors

Dr. Armin Hofmann
Product manager Measuring Instrumentation
LAUDA DR. R. WOBSER GMBH & CO. KG
Pfarrstr. 41-43
97922 Lauda-Königshofen, Germany
E-Mail: dr.hofmann@lauda.de

Ivanka Atanasova-Hoehlein
Dipl. Chemikerin
Siemens AG, Trafowerk Nürnberg
Katzwangerstr. 150
90461 Nürnberg
E-Mail: ivanka.hoehlein-atanasova@siemens.com

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