THERMAL AGEING OF MINERAL INSULATING OIL AND KRAFTS PAPER

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A dynamic heating experiment for ageing oil and paper and examination of the influence of temperature on ageing and degradation of insulating paper in transformer oil.

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Despite the apparent mechanical weakness of oil and paper they are effective insulators, especially in combination. This is exemplified in the observed synergism of paper impregnated with oil: the dielectric strength of paper and oil on their own is 40 and 12 kV per mm respectively, however their dielectric strength in combination is 64 kV per mm, which is a significant improvement.

Even in ideal conditions, oil and paper will degrade, or 'age', as their useful service lives is finite. The actual processes involved depend on the operating conditions of the equipment, but the rate of ageing is normally a function of temperature and moisture. Both oil and paper will age rapidly at high temperatures and moisture acts as a catalyst for the ageing of oil. There are also other catalysts present in a transformer, which are responsible for oil ageing; these include copper, paint, varnish and oxygen. The principal mechanism of oil ageing is oxidation, which results in acids and other polar compounds being formed. These oxidation products will have a deleterious effect on the paper degradation processes.

Thermal degradation of Kraft insulation paper will take place in transformers at the normal operating temperature of 60 to 90°C. This degradation is accelerated at higher temperatures, especially if the unit overheats or develops hot spots. As a result, the useful life of the transformer may be significantly reduced. Although damaged or degraded paper may have acceptable electrical properties its mechanical properties might be sufficiently weakened so that it can no longer withstand mechanical vibrations.

INSULATING OIL

Insulating oil can be classified as paraffinic or naphthenic, which is mostly related to the crude oil used at the refinery. Paraffinic oils have poor low temperature properties and low solvent power towards oxidation products, especially sludge. This may lead to precipitation of sludge on the windings and blockages in the ducts. Conversely, oil oxidation products are soluble in naphthenic oil.

The resistance of oil to oxidation is a crucial factor in its service life and it depends on the presence of antioxidants. Some oils will contain these naturally and they can be enhanced by the refining processes, typically hydrogenation. Oils that are deficient in natural antioxidants can be improved by the addition of oxidation inhibitors.

INSULATING OIL AGEING

The ageing mechanisms of oil are complicated. In general oxygen reacts with certain hydrocarbons by a free radical process, which is a chain reaction mechanism, generates hydroperoxides. Hydroperoxides are not stable and decompose to form ketones and water. Ketones can be oxidised further to form carboxylic acids or cleaved to make aldehydes.

Oxidation inhibitors, whether naturally occurring or added after refining, retard the oxidation mechanisms by destroying free radicals and initiators or by reacting with peroxides to form more benign products. Free radical reactions will take place more quickly in the presence of catalysts such as copper and aluminium.

The choice of base oil is extremely important in developing inhibited oils. The effectiveness of inhibition is measured by performing an oxidation stability test. The current oxidation stability test takes place in the presence of excess oxygen. This is in contrast to service conditions in electrical equipment where available oxygen is never greater than that given by air saturation in oil. However, the test is designed to accelerate the ageing and therefore, it is conducted at high temperature with excess oxygen and metal catalyst for 164 hours.

INSULATING PAPER

The paper used to insulate electrical plant is made from the Kraft process and has a matted brown appearance. The thickness of paper used varies from 30 to120μm and several layers (up to 15) are wrapped around each copper conductor to insulate each turn from the next. The natural moisture content of the paper is approximately 6% and the insulation paper used in a transformer has to be dried before service. The degree of polymerisation (DP) is reduced to about 950 during the drying process, which can take 10-16 days in a vacuum at 95-100°C or 2-3 days in a light oil vapour at 120-140°C. The final moisture content of the paper is typically less than 0.1%.

Kraft paper is used in preference to other paper types because of its high purity. It is prepared for the electrical industry to a specific electrical resistivity, by ensuring there are no metal ions present within the pulp that could reduce its resistivity. Kraft paper is a cheap source of insulation, which is an important consideration in the construction of a transformer given the quantity involved (12 tonnes in a typical three-phase transformer).

Paper deteriorates inside electrical transformers and leaves it vulnerable to stresses generated by thermal, mechanical and electrical transients. Water, heat and oxygen degrade the paper, reducing the DP from an initial value of approximately 1300 and the strength of the paper decreases with DP. The paper is expected to last the lifetime of the transformer (25-40 years), but at a DP of 150-200 the mechanical strength of the paper can be reduced to

Stress	Ageing Process
Electrical	Electrical gradient within system
Thermal	High temperature, resistivity loss, chemical instability of oil or paper
Mechanical	Vibration
Environmental	Moisture, chemical reactions, oxidation

Table 1.

Thermal Ageing of Mineral Insulating Oil and Krafts Paper (Cont. from Page 57)

20% of its initial value. This point is regarded as the end of life criterion for transformer insulation, because the paper loses its mechanical strength, although its dielectric constant is not greatly affected. Degradation of the paper can cause the transformer to fail as follows: the brittle paper may break away from the transformer windings and block ducts; local carbonising of the paper increases the conductivity to cause overheating and conductor faults.

OIL AND PAPER AGEING

The role of electrical insulation is to provide electrical insulation, mechanical support and heat dissipation. As previously noted, the failure of paper is irreversible, whereas oil can be reclaimed or replaced. The destruction of paper insulation in service is mainly due to the presence of degrading stresses, such as electrical, thermal, mechanical and other stresses associated with its environment. In general they can be summarised as shown in Table 1 above.

The initial drying process, required when manufacturing a transformer, has the immediate effect of reducing the DP of the paper. In service, thermal stress further reduces the DP and oxidises the oil. The condition of the oil can be monitored regularly by sampling the oil and analysing as per tests recommended in IEC 60422. Depending on the results, corrective actions are recommended and the oil can be replaced or reclaimed as and when necessary.

Evaluating the condition of the paper is less straightforward. The removal of paper from a transformer is extremely difficult and may lead to the failure of the unit. Paper monitoring, therefore, has to be carried out indirectly. Certain paper degradation products such as moisture, CO, CO_2 and furanic compounds migrate from the paper into the oil and can be used as probe compounds to assess the condition of the insulating paper. Furanic compounds, in particular, are normally characteristic of ageing of the paper while moisture, CO and CO_2 may also be formed from thermal degradation of the insulating liquid.

EXPERIMENTAL WORK

Paper and oil are aged under laboratory conditions using dynamic heating program in sealed tube as described earlier. The oil was Nynas Nytro 11EN containing 0.3% DBPC and 25 mg/kg Benzotriazol and the paper was Kraft paper electrical grade wrapped in several layers around a length of 5 cm of copper conductor. The paper was dried to less than 0.5% moisture. The samples are aged from 70 to180ºC for 24 hrs and then the gas content and furfural content was measured.

RESULTS AND DISCUSSIONS

The results for gas formation are shown in Table 2. Generally it is indicating that fault gases are formed in measurable level at temperature of above 140ºC and increasing with increase of temperature.

The degree of polymerisation of paper starts decreasing at a temperature of 120 ºC. This decrease of DP is faster with increase of temperature, reaching the value characteristic of the end of life of paper, at a temperature of 180 ºC. The correlation between 2FAL and 5HMF concentration in oil, and the corresponding DP value of the paper indicates that once the DP value reached 450, production of 2FAL and 5HMF starts. However, concentration of furfural absorbed by paper can be related to DP of less than 900, which means that detecting furanic compounds absorbed by the paper, is a better indication of DP depreciation. On the other hand, the concentrations of furanic compounds in paper, are about 150 times greater than the corresponding concentration in the oil, which suggest, that the partition coefficient of these compounds, between paper and oil, are much more favourable to the paper, than to the oil. We highlight the great importance of furanic compound analysis in oil, as a tool to monitor the ageing process of the paper. However, the correlation between the concentration in oil of the most common furanic compounds (namely the furfural) and the DP value of the insulating paper it is not easy to establish, because it depends on many factors such as: range of temperature, model of construction of the transformer, type of the insulating paper (kraft paper, thermally up-graded paper,

Tem.	H2		CO		CO2 ml/l		CH4		C2H6		C2H4		C2H2	
ºC	B	S	B	S	B	S	B	S	B	S	B	S	B	S
70	<4	<5	<28	<30	2.0	2.2	<1	<1	<1	<1	2	2	<3	<4
80	<4	15	<28	35	1.5	1.8	<1	1	<1	<1	3	2	<3	<3
90	<4	<4	<25	<25	1.7	2.2	<1	<1	<1	<1	2	2	<3	<3
100	<5	6	<30	<30	1.9	2.0	<1	<1	<1	<1	2	2	<4	<4
110	5	4	<30	<30	3.3	2.6	1	1	<1	<1	3	2	<4	<4
120	10	8	<30	56	2.7	8.1	<1	1	<1	<1	1	2	<4	<4
130	16	22	57	152	2.2	3.4	2	2	<1	<1	2	3	<4	<4
140	48	46	167	302	2.3	3.3	5	7	2	1	9	10	<4	<3
150	144	166	720	899	3.2	6.1	27	44	3	6	18	22	<4	<4
160	126	188	789	1106	2.7	7.0	40	58	10	17	21	28	<3	<4
170	122	194	726	1080	2.5	6.8	39	61	10	17	18	24	<4	<5
180	167	210	1048	1323	4.0	8.4	60	72	16	22	24	27	<5	<5

Table 2
Gas content in oil, as µl /l (for all gases exception made for CO_2) of aged: B= Blank (oil sample) and S= Oil+Paper sample.

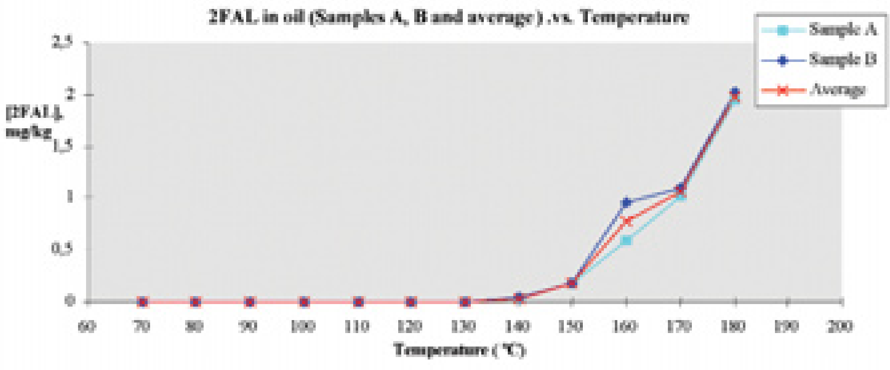

Figure 1: Furfural formation as mg/kg$_{oil}$ as function of temperature

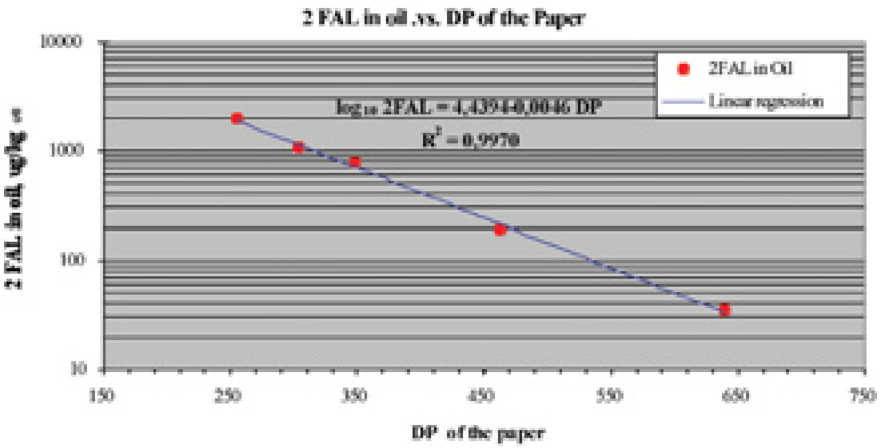

Figure 2: Furfural content in oil as µg /kg$_{oil}$, versus degree of polymerisation of the paper

other synthetic solid insulating materials, like Nomex), type of oil, and usual working conditions of the transformer, and so on. The results for furfural formation as function of temperature are shown in figure 1. The results indicating fufurals are formed at significant level at temperature of 150°C. No detectable amount of furans was detected in the blank oil samples. Based on furfural results obtained, for this work, the relation between furfural and DP of the paper are calculated and shown in figure 2, (see next page) which is comparable with previous modes.

Moisture is generated at temperature of over 80°C from degradation of insulating oil, however, at temperature of 170°C paper generates a noticeable amount of moisture.

ANALYSIS OF FURFURAL

Oil samples can be analysed for furfural (FFA) content using the method described in IEC 61198. Although the measurement of FFA in oil is relatively simple, interpreting the results is complex. It is essential that there is an understanding of the kinetics involved in the formation of the FFA before any attempt is made to assess the condition of the paper or to estimate its remaining life. At low temperatures moisture and CO_x are the more dominant products of ageing, at intermediate temperatures furanic compounds and sugars are produced and at higher temperatures carbon deposits and tar are produced. FFA is not detected at high temperatures due to its rapid breakdown after formation. Several authors have studied paper ageing and have attempted to relate FFA analysis to DP of the paper. The laboratory studies used several techniques for degrading the paper, however a linear relation between log of FFA and DP has generally been observed. De Pablo reported the relation between FFA and DP as:

$$DP = \frac{7100}{8.88 + FFA}$$

The FFA concentration is expressed as mg/kg of oil. Assuming the minimum acceptable value of DP for a unit is 200, then using the above formula the FFA content of the unit is 30 ppm. In service it is unlikely that all the winding paper will be degraded to the same extent, since not all the paper is subjected to the same conditions.

The formula is modified based on transformer conditions and an assumption that 20% of winding paper and the inner paper layer degrade twice as fast as the rest of the paper. The revised formula is:

$$DP = \frac{800}{(0.186 \times FFA) + 1}$$

Provided that there is sufficient knowledge of the unit concerned, it is possible to infer the DP of the paper from the FFA concentration in the oil.

There are several important factors to be considered when using FFA results to calculate DP:

- Laboratory experiments have shown that FFA is unstable in the presence of copper, dimethyl cyan (released during the ageing of thermally upgraded paper) and heat.
- The FFA can be absorbed by paper
- Transformer load (temperature) may affect the FFA concentration in the oil.

Therefore, it is only possible to estimate the state of the paper by monitoring the changes of concentration of furanic compounds in the oil if the sampling is strictly controlled. It is also possible to use the relationship to estimate the quantities of 2-furaldehyde that can be generated during the lifetime of the paper.

CONCLUSION

Oil and paper degrade with time under the influence of temperature and moisture. The lifetime of the oil can be monitored by regular sampling and analysis using standards/guidelines for corrective action. Analysis of the furanic compounds dissolved in the insulating oil can be used for condition monitoring of paper insulating systems and it can provide complementary information to dissolved gas analysis (DGA). Care must be taken not use FFA in isolation or as a way of making an instant measurement of transformer condition. FFA should be used as a complement to DGA and other monitoring techniques to give a better overall picture of the condition of the paper and insulating oil before any decision is made on action to be taken.