Revised IEC Standard for Maintenance of In-Service Insulating Oil

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Abstract

For reliable operation of oil-filled electrical equipment, monitoring and maintenance of insulating liquid is essential. Mineral insulating oil is the most widely used insulating liquid for cooling and insulation in oil-filled electrical equipment. The characteristics of the oil, supplied as unused, may change during service life. Therefore, the oil quality should be monitored regularly during its service life.

In many countries power companies and electrical power authorities have established codes of practice for this purpose. In general these cover monitoring guidelines and corrective actions depending on the oil status. If a certain amount of oil deterioration is exceeded then the possibility and risk of premature failure should be considered. While the quantification of the risk can be very difficult, a first step involves the identification of potential effects of increased deterioration.

IEC60422 is the guide for supervision and maintenance of mineral insulating oils. This standard is now revised to take account of changes in oil and equipment technology and has due regards, for the best practices currently in use, worldwide. Changes are also made to use current methodology and comply with requirements and regulations affecting safety and environmental aspects.

Introduction

Oil in electrical equipment deteriorates in service due to the conditions of use. The reliable performance of oil in insulation system depends on the basic character of the oil, which may affect performance of the equipment. A variety of processes occur, some inter-related, which degrade the oil. These processes include: oxidation; contamination by water, particles or fibers; electrical arcing or discharge; and local or general overheating.

Oxidation of the oil will occur in all equipment where it is in contact with air. In such equipment, oxidation of the oil will occur gradually and naturally over many years.

Oxidation is accelerated as operating temperatures of the oil increase. Oxidation can also be accelerated by the presence of catalysts such as metals or metallic compounds. The cumulative effects of oxidation on the oil are to darken the oil, produce water and acids, and in the extreme, produce sludge. The production of water and acids can lead to corrosion of metal surfaces, particularly above the oil surface and can attack cellulose material, resulting in loss of mechanical strength and possible breakdown.

If the oil reaches an advanced state of oxidation, insoluble products are generated, which result in sludge formation in the oil. The produced sludge is soluble in the oil depending on the type of oil and once reached to saturation point it will precipitate. Generally, sludge is more soluble in naphthenic oil and less soluble in paraffinic oil. The sludge deposits itself on windings and other parts, blocking ducts and reducing cooling efficiency. The overheating of the oil and windings, and the oxidation of the oil increase cumulatively, leading to possible breakdown.

Early warning of the onset of oil oxidation is provided by monitoring of the colour and appearance of the oil, regular testing for acidity levels in the oil, monitoring moisture levels in the oil and visual inspection during maintenance for signs of sludgy deposits on internal surfaces of equipment.

IEC60422 (1) is a guide for the supervision and maintenance of mineral insulating oil in electrical equipment. This standard is used worldwide and is currently under revision. The purpose of the revision of this standard is to bring it in line with current methodology, best practice and compliance with requirements and regulations affecting safety and environmental issues.

Oil Contamination

Insulating oil in electrical equipment, depending on design, is in contact with air and other material used in construction of the equipment and therefore, can easily be contaminated. In general, presence of foreign material in the oil can be regarded as contamination. Some of these contaminants may affect the electrical or other properties of the oil.

Contamination by Moisture

Contamination can occur from degradation of the oil by oxidation, degradation of cellulose in the equipment and ingress due to breathing of the equipment in service or during maintenance or repair work. Water is soluble in oil within certain temperature- and acidity dependent limits. If these limits are exceeded the oil becomes saturated and free water will appear in the form of cloudiness or visible droplets. Dissolved water may or may not affect the electrical properties of the oil. However, dissolved water in the presence of other contaminants, particularly fibres, can significantly reduce the electrical strength of oil. Free water, further reduces the electrical strength of the oil as well as indicates excessive moisture content in the oil.

In transformers, or other equipment containing paper insulation, the moisture is contained in both the oil and the paper. The paper contains much more of the moisture than the oil, typically over 99% of the total water content being in the paper. High moisture content of paper is one of the factors which reduces the life of the paper insulation, and hence the life of the equipment. Maintaining low moisture content is therefore more important in equipment containing paper insulation such as transformers. Monitoring of moisture content is achieved by routine laboratory analysis for dissolved moisture, and by visual inspection for signs of free moisture.

Contamination by Particles or Fibres

Contamination can occur from particulate or fibrous matter taken up by the oil from the components of the equipment itself, from arcing, fault degradation products in the equipment, or ingress during maintenance or repair.

Particle or fiber contamination can reduce the electrical strength of the oil, particularly in the presence of moisture. Monitoring is achieved by laboratory testing for electric strength, which reduces with high particle content, and by visual inspection for particulate contamination.

Electrical Breakdown or Arcing

Electrical breakdown or arcing under oil produces gases and arc products such as carbon or metallic particles. The degradation of the oil results in a reduction in electrical strength, accelerated oxidation and higher acidity.

This type of degradation is to be expected in equipment having an arc extinguishing function such as circuit breakers or tapchanger diverter switches. The design of this equipment includes an allowance for the degradation of the oil.

Oil degradation in equipment that does not have an arc extinguishing function, such as a transformer main tank or selector, is obviously undesirable and indicates the presence of a fault or malfunction.

The ageing process of insulating paper is accompanied by the production of several oil soluble by-products. These by-products are carbon monoxide, carbon dioxide, water and furanic compounds. The production of carbon monoxide and carbon dioxide can be monitored by DGA (2). However, production of these two gases can rise from either paper ageing or insulating oil ageing. Trend analysis of the level of Furanic compounds (3) in the oil (FFA analysis) may provide an early indication of paper degradation.

Revised Standard

IEC60422 has been revised to take account of changes in oil and equipment technology and to have due regard for the best practices currently in use worldwide. In general the action limits for all oil test have been revised and changes made where necessary to enable users to use current methodology and comply with requirements and regulations affecting safety and environmental aspects.

Oil Testing

The tests for in-service oil are divided into three groups as:

Group 1: minimum tests require to monitor the oil and to ensure that it is suitable for continued service.

Group 2: These are additional tests that may be used to obtain further specific information about the quality of the oil and may be used to assist in the evaluation of the oil for continued use.

Group 3: These tests are used mainly to determine the suitability of the oil for the type of equipment in use and to ensure compliance with environmental and operational considerations.

Individual tests for each group are shown in Table 1. It should be noted if test results for group one are not exceeding recommended action limits, usually no further tests are considered necessary until the next regular period for inspection.

Significance of Tests

Although a large number of tests can be applied to mineral insulating oil in electrical equipment, the tests listed in Table 1 are considered sufficient to evaluate the condition of the oil in service and to establish whether the condition of the oil is adequate for continued operation. Corrective actions, based on the results, are then suggested.

Acidity

The acidity of a used oil is due to the formation of acidic oxidation products. Acids and other oxidation products will, in conjunction with water and solid contaminants, affect the dielectric and other properties of the oil. Acids have an impact on the degradation of cellulosic materials and may also be responsible for the corrosion of metal parts in a transformer.

The rate of increase of acidity of oil in service is a good indicator of the ageing rate. The acidity level is used as a general guide for determining when the oil should be replaced or reclaimed.

Water Content

Oil serves as a water-transferring medium within a transformer. In a transformer, the total mass of water is distributed between the paper and the oil such that the bulk of water is in the paper. Small changes in temperature significantly modify the dissolved water content of the oil but only slightly modify the water content of the paper.

Thus, for the proper interpretation of moisture content the analytical results need to correct the water content of the oil at a given sampling temperature to the content at a defined temperature. For practical reasons, the defined temperature is set at 20ºC, since below 20ºC the rate of diffusion of water is too slow to achieve equilibrium in operational equipment.

The correction formula, as demonstrated by several independent studies (Figure 1), is: $\mathbf{f=2,24e^{(-0,04ts)}}$ (1)

where **f** is the correction factor and $\mathbf{t}_s$ is the oil sampling temperature, in Celsius. This formula is applicable only to operating temperature of above 20 C and for temperature of below 20 C, calculation of percentage of saturation is suggested.

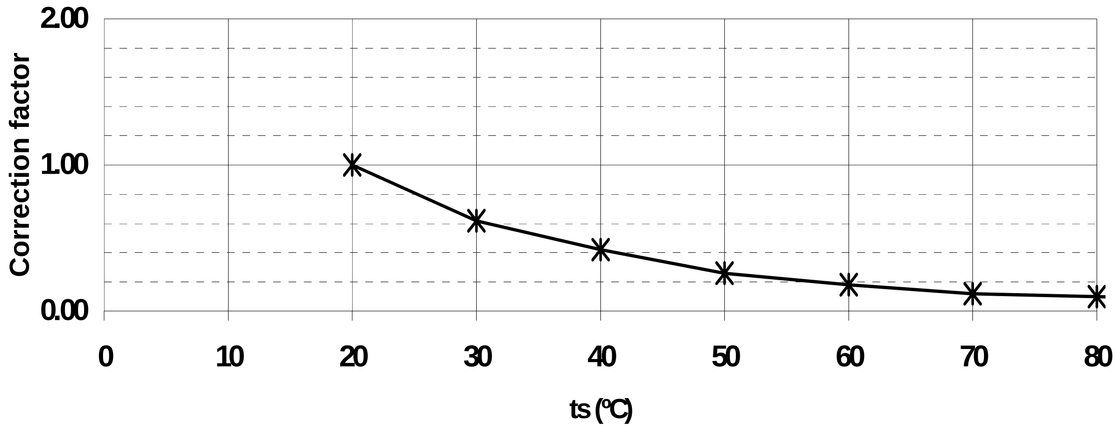

Figure 1
Temperature Correction Graph

The water solubility of a typical, unused mineral insulating oil is given by the formula:

$$\textbf{Log } W_s = 7{,}0895 - (1567 / T) \quad (2)$$

Where W_s is the solubility of water in unused mineral oil in mg/kg and **T** is the absolute temperature of the oil in Kelvin.

And

$$\textbf{\% Saturation} = (\text{mg/kg of water} / W_s) \times 100 \quad (3)$$

By way of a guide, the condition of cellulosic insulation referred to oil percent saturation is given in Table 2.

Breakdown Voltage

Dry and clean oil exhibits an inherently high breakdown voltage. Free water and solid particles, the latter particularly in combination with high levels of dissolved water, tend to migrate to regions of high electric stress and reduce breakdown voltage dramatically. The measurement of breakdown voltage, therefore, serves primarily to indicate the presence of contaminants such as water or particles.

A low value of breakdown voltage can indicate that one or more of these are present. However, a high breakdown voltage does not necessarily indicate the absence of all contaminants.

Dielectric Dissipation Factor and Resistivity

These parameters are very sensitive to the presence of soluble polar contaminants, ageing products or colloids in the oil. Changes in the levels of the contaminants can be monitored by measurement of these parameters even when contamination is so slight as to be near the limit of chemical detection.

Acceptable limits for these parameters depend largely upon the type of equipment. However, high values of dielectric dissipation factor, or low values of resistivity, may deleteriously affect the power factor and/or the insulation resistance of the electrical equipment.

There is generally a relationship between DDF and resistivity, with resistivity decreasing as DDF increases. It is normally not necessary to conduct both tests on the same oil and generally DDF is found to be the more common test. Resistivity and DDF are temperature dependent and Figure 3 illustrates typical changes of resistivity with temperature for insulating oils that are virtually free from solid contamination and water.

Useful additional information can be obtained by measuring resistivity or DDF at both ambient temperature and a higher temperature such as 90°C.

Oxidation Stability

The ability of mineral electrical insulating oil to withstand oxidation under thermal stress and in presence of oxygen and a copper catalyst is called oxidation stability. It gives general information about the life expectancy of the oil under service conditions in electrical equipment. The property is defined as resistance to formation of acidic compounds, sludge and compounds, influencing the dielectric dissipation factor (DDF) under given conditions. For oils complying with IEC 60296 (19) these conditions are detailed in IEC 61125 method C (10) and the limits of acceptable performance in IEC 60296.

The property depends mainly on the refining process and how it is applied to a given feedstock. Refined mineral oils contain, to a varying degree, natural compounds acting as oxidation inhibitors. These are known as natural inhibitors. Oils containing only natural inhibitors are designated as uninhibited oils.

Synthetic oxidation inhibitors can be added to enhance the oxidation stability. In transformer oils mainly the phenolic type is used and the common and generally accepted compounds are 2,6-di-tert-butyl-paracresol (DBPC) and 2,6-di-tert-butyl-phenol (DBP). The efficiency of added inhibitors will vary with the chemical composition of the base oil.

Inhibited oils have a different oxidation pattern compared to uninhibited oils. At the beginning of service life the synthetic inhibitor is consumed with little formation of oxidation products. This is referred to as the induction period. After the inhibitor is consumed the oxidation rate is determined mainly by the base oil oxidation stability.

The common and easy way to monitor the inhibitor consumption is to measure the inhibitor concentration according to IEC 60666 (9).

Oxidation Stability Tests

To determine "remaining lifetime" the oxidation stability tests specified in IEC 61125 method C (10) may be used. As these tests are designed for unused oils, interpretation of test results may be difficult. Although not widely used, IEC 61125 method B (10) can be beneficial in determining the remaining induction period for inhibited oils.

Sediment and Sludge

Sediment is insoluble material present in the oil.

Sediment– includes:

- Insoluble oxidation or degradation products of solid or liquid insulating materials;
- Solid products arising from the conditions of service of the equipment: carbon, metal, metallic oxides;
- Fibres, and other foreign matter, of diverse origins.

Sludge is a polymerised degradation product of solid and liquid insulating material. Sludge is soluble in oil up to a certain limit, depending on the oil solubility characteristics and temperature. At sludge levels above this, the sludge is precipitated, contributing an additional component to the sediment. The presence of sediment and/or sludge may change the electrical properties of the oil, and in addition, deposits may hinder heat-exchange, thus encouraging thermal degradation of the insulating materials.

Sediment and sludge should be measured according to the method described in IEC 61125 method C without submitting the oil sample to the oxidation process, by filtration of the oil for sediment content and by adding n-hepatne and filtration of sludge.

Interfacial Tension (IFT)

The interfacial tension between oil and water provides a means of detecting soluble polar contaminants and products of degradation. This characteristic changes fairly rapidly during the initial stages of ageing but levels off when deterioration is still moderate. A rapid decrease of IFT may also be an indication of compatibility problems between the oil and some transformer materials (varnishes, gaskets), or of an accidental contamination when filling with oil. For overloaded transformers the deterioration of materials is rapid and IFT is a tool for detection of deterioration.

Particle Count

The presence of particles in insulating oil in electrical equipment may have a number of possible sources. The equipment itself may contain particles from manufacturing and the oil may contain particles from storage and handling if not properly filtered. Wear, and the ageing of oil and solid materials may produce particles during the service life of equipment. Localised overheating over 500 C may form carbon particles. The carbon particles produced in the on-load tap-changer diverter switch may migrate by leakage into the bulk oil compartment to contaminate the oil-immersed parts of the transformer. A typical source of metallic particles is wear of bearings of the pumps.

The effect of suspended particles on the dielectric strength of insulating oil depends on the type of particles (metallic, fibres, sludge etc.) and on their water content.

Flash Point

Breakdown of the oil caused by electrical discharges or prolonged exposure to very high temperature may produce sufficient quantities of low molecular weight hydrocarbons to cause a lowering of the flash point of the oil.

Pour Point

Pour point is a measure of the ability of the oil to flow at low temperature. There is no evidence to suggest that this property is affected by normal oil deterioration. Changes in pour point can normally be interpreted as the result of topping-up with a different type of oil.

Density

Density may be useful for type identification. In cold climates, the density of oil may be important in determining its suitability for use. For example, ice crystals formed from separated water may float on oil of high density and lead to flashover on subsequent melting. However, density is not significant in comparing the quality of different samples of oil. There is no evidence that density is affected by normal oil deterioration.

Viscosity

Viscosity is an important controlling factor in the dissipation of heat. Ageing and oxidation of the oil tend to increase viscosity. Viscosity is also affected by temperature. Normal ageing and oxidation of the oil will not significantly affect its viscosity. Only under extreme conditions of corona discharges or oxidation may this occur.

Polychlorinated biphenyls (PCBs)

These are a family of synthetic chlorinated aromatic hydrocarbons, which have good thermal and electrical properties. These properties combined with excellent chemical stability made them useful in numerous commercial applications. However, their chemical stability and resistance to biodegradation has given cause for concern in terms of environmental pollution. This increasing concern over the environmental impact of PCBs has progressively restricted their use since the early 1970s and their use in new plant and equipment was banned by international agreement in 1986. Unfortunately the use of common handling facilities has led to widespread contamination of mineral insulating oil.

The PCB content of oil in new equipment should be measured to confirm that the oil is PCB free. Thereafter whenever there is a risk of potential contamination (oil treatment, transformer repairs, etc.) the oil should be analyzed and if PCB content is found to exceed defined limits appropriate action should be taken.

Corrosive Sulphur

Sulphur is present in refined oils depending on the degree of refining, type of refining and crude oil used. The sulphur compounds remaining in refined oil are relatively stable and impart oxidation stability.

The determination of corrosive sulphur in the oil in service is seldom necessary under normal conditions as oils supplied to most standards and specifications should be free from corrosive sulphur.

At high temperature, sulphur compounds may decomposes on hot metal surfaces to produce metal sulphides that can affect the electrical properties of the oil and provide nuclei for discharge and gas inception if they become detachable and dispersed in the oil. After an event with such temperatures a corrosive sulphur test may be used to ensure freedom from corrosive attack under continued service.

Evaluation of Oil in Service

Insulating oil in service is subjected to heat, oxygen, water and other catalysts, all of which are detrimental to the properties of the oil. In order to maintain the quality of the oil in service, regular sampling and analysis should be performed.

Often the first sign of oil deterioration may be obtained by direct observation of the oil clarity and colour through the conservator’s visor. From an environmental point of view, this simple and easy inspection can be also used to monitor leakage and spills of oil to the surrounding soil.

The interpretation of results, in terms of the functional deterioration of the oil, should be done by experienced personnel based on the following elements of Risk Management and Life Cycle Analysis:

- Characteristic values for the type and family of oil and equipment, developed by statistical methods;
- Evaluation of trends and the rate of variation of the values for a given oil property;
- Normal, or typical values, for “fair” or “poor” for the appropriate type and family of equipment.

In the case of oil contaminated with PCB, environmental impact is a critical factor to consider, as are local regulations. If it is suspected that oil has become contaminated with PCB specific analyses should be undertaken and interpretation of the results should be used in risk assessment to take into account prevention and mitigation of potential damage to the environment and to avoid unreasonable risks for staff and the public.

Classification of Oil in Service

It is virtually impossible to set hard and fast rules for the evaluation of oil in service and recommend a corrective action. Classification and any consequent corrective action should only be taken after due consideration of the results of all tests. The trend of such results over a period of time is considered essential information when arriving at a final decision.

According to local or current industrial experience, oils in service may be classified as “good”, “fair” or “poor” based on the evaluation of significant properties and their ability to be restored to the characteristics desired. Table 3 provides guidance to assist in this classification process.

Good
Oil in normal condition, continue normal sampling

Fair
Oil deterioration detectable, more frequent sampling recommended

Poor
Oil deterioration abnormal, immediate action advisable

Results for test limits together with corrective action are shown in Table 3.

Oil handling storage, oil purification and oil PCB destruction are also discussed and explained in this revised standard as guide for supervision and maintenance of insulating oil.

Conclusion

International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). IEC60422 "Guide for the supervision and maintenance of mineral insulating oil in electrical equipment" is revised to take into account of changes in oil and equipment technology and to have due regards for the best practice currently in use. The action limits for all tests have been revised and changes made where necessary to enable the users to use current methodology and comply with requirements and regulations affecting safety and environmental aspects. The produced document has the form of recommendations for international use and will be published in the form of a standard. The document is currently in CDV format circulated to the national committees for voting.

Table 1
Test for mineral insulating oils

Group 1 tests (Routine tests)	
Colour and appearance (4)	ISO 2049
Breakdown voltage (5)	IEC 60156
Water content (6)	IEC 60814
Acidity (neutralization value) (7)	IEC 62021
Dielectric dissipation factor (DDF) or resistivity (8)	IEC 60247
Inhibitor content (9)	IEC 60666
Group 2 tests (Complementary tests)	
Sediment and sludge (10)	IEC 61125 method C
Interfacial tension (11)	ISO 6295
Particles (particle count) (12)	IEC 60970
Group 3 tests (Special investigative tests)	
Oxidation stability (10)	IEC 61125
Flash point (13)	ISO 2719
Compatibility (10)	IEC 61125
Pour point (14)	ISO 3016
Density (15)	ISO 3675
Viscosity (16)	ISO 3104
Polychlorinated biphenyls (PCBs) (17)	IEC61619
Corrosive sulphur (18)	DIN 51353

Table 2
Guidelines for interpreting data expressed in percent saturation

Percent saturation water in oil, adjusted to 20 C	**Condition of cellulosic insulation**
0 – 5 %	Dry insulation
6 – 20 %	Moderate wet, low numbers indicate fairly dry to moderate levels of water in the insulation. Values toward the upper limit indicate moderately wet insulation
21 – 30 %	Wet insulation
> 30 %	Extremely wet insulation

Table 3
Tests and recommended action limits

Property	**Category**	**Recommended Action Limits**		
		Good	**Fair**	**Poor**
Acidity mgKOH/g	>72.5 KV <72.5 KV	<0.1 <0.15	0.1-0.15 0.15-0.3	>0.15 >0.3
Breakdown Voltage KV	>170 KV 170-72.5 <72.5 KV	>60 >50 >40	60-50 50-40 40-30	<50 <40 <30
Colour	All	All Clear without visible contamination	l	Dark and/or turbid
Dielectric Dissipation Factor at 90 C	>72.5 KV <72.5 KV	<0.1 <0.1	0.1-0.2 0.1-0.5	0.2 0.5
Flash point C	All	Maximum decrease of 13 C		
Inhibitor content %	All	Minimum 40-60 % original value		
Interfacial Tension mN/m	All	>28	22-28	22
Particles (counting & sizing)		CIGRE 157 report (20)		
PCBs mg/kg	All	Bellow defined limit		
Resistivity at 90 C, G .m	>72.5 KV <72.5	>10 >3	1-10 0.2-3	<1 <0.2
Sediments & Sludge %	All	No sediment or precipitable sludge		
Water content corrected to 20 C	>170 170-72.5 <72.5	<5 <5 <10	5-10 5-15 10-25	>10 >15 >25

References

1. IEC60422: *"Guide for the supervision and maintenance of mineral insulating oils in electrical equipment".*

2. IEC 60599: *"Mineral oil-impregnated electrical equipment in service - Guide to the interpretation of dissolved and free gases analysis".*

3. IEC 61198: "*Mineral insulating oils - Methods for the determination of 2-furfural and related compounds".*

4. ISO 2049: *"Petroleum products – Determination of colour"* (ASTM scale).

5. IEC 60156: *"Insulating liquids - Determination of the breakdown voltage at power frequency"* - Test method.

6. IEC 60814: Insulating liquids - Oil-impregnated paper and pressboard - *"Determination of water by automatic coulometric Karl Fischer titration".*

7. IEC 62021: *"Insulating liquids – Determination of acidity by automatic potentiometric titration"* – Test method – Part 1: Mineral insulating oils.

8. IEC 60247: *"Measurement of relative permittivity, dielectric dissipation factor and d.c. resistivity of insulating liquids".*

9. IEC 60666: *"Detection and determination of specified anti-oxidant additives in insulating oils".*

10. IEC 61125: Unused hydrocarbon based insulating liquids - *"Test methods for evaluating the oxidation stability".*

11. ISO 6295: Petroleum products – Mineral oils – *"Determination of interfacial tension of oil against water"* – Ring method [non-equilibrium].

12. IEC 60970: *"Methods for counting and sizing particles in insulating liquids".*

13. ISO 2719: Petroleum products and lubricants – *"Determination of flash point – Pensky-Martens closed cup method".*

14. ISO 3016: Petroleum products – *"Determination of pour point".*

15. ISO 3675: Crude petroleum and liquid petroleum products – *"Laboratory determination of density"* – Hydrometer method.

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Biographies:

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