Mineral oil particle analysis - why is it included in NRS 079-1?

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Transformer oil fulfills two main tasks in a transformer, namely cooling and insulation. These abilities will decrease as the oil deteriorates or becomes contaminated.

The immediate, though infrequent, result of severe contamination with various contaminants is dielectric failure and a short circuit. A third and very valuable property of the transformer oil, is the fact that it is a carrier of information on the status of the insulation system.

Insulating oils, once used in transformers, switchgear, capacitors and cables will change with respect to their physical and chemical characteristics. This happens due to the fact that the oil is exposed to various conditions during operation such as:

- Increased temperatures
- Absorption of gases, mainly oxygen
- Absorption of water from the atmosphere
- Particles such as metal, fiber, dust and other

These changes may be significant and may lead to costly breakdown of oil insulated devices. Ageing of the insulation system is not limited to physical changes only, but also to chemical changes, which may result in the destruction of transformers and other power equipment.

Some of the tests that are carried out on transformer oil will specifically analyse the chemical and physical characteristics, for example, particulate contamination analysis, tan delta (dissipation factor) and dielectric strength (breakdown voltage).

The factors mentioned will influence the oil to such an extent that an increase in tan delta, increase in particulate contamination and a decrease in the dielectric strength is expected.

**Breakdown voltage or dielectric strength**

The breakdown voltage indicates the ability of oil to withstand electrical stress. A high dielectric strength value does not necessarily indicate an absence of all contaminants such as conducting particles in the insulation oil. The dissipation factor is the measurement of the leakage current through the oil. The dielectric dissipation factor is very sensitive to the presence of soluble contaminants, ageing products or colloids. The breakdown voltage is less of a criterion for the judgment of the quality of insulation liquid itself, but more for the pollution by foreign particles (e.g. fibers) and water. This test indicates the physical state of the oil only, so it is advisable that this test be carried out in conjunction with the chemical tests, which would determine the presence of contaminants.

**Dissipation factor or tan delta**

Dissipation factor (tan delta) is the measurement of the loss angle and depends on ions in the oil. New oil should have a very low value, which will increase with the use of the oil. Water will not affect this property, but might form stable complexes, which will give higher tan delta values. As oil ages, the oxidation of the oil will affect the tan delta and an increase in the tan delta value will be observed. The oxidation process entails the formation of oxides, which forms acids, and these acids are responsible for the degradation of the cellulose material or paper insulation as well as the metal components of the transformer. One of the by-products of the insulation and metal breakdown is sludge, which will deposit on various parts of the transformer and cause an uneven distribution of heat, which may result in the formation of hot spots resulting in eventual breakdowns. Each increase of 10ºC will reduce the life expectancy of the solid insulation by 50%.

According to Baur[1], the tan delta will give an indication of the degree of cleanliness of the oil. Oxidation products will have an effect but so will lacquers and other materials that have dissolved in the oil.

Transformer oil should always be clean and dry. When an oil filled transformer is in operation some power is lost by the dissipation electrical energy caused by the conduction process within the oil. Tan delta (dissipation factor) is one of the most useful measures to determine the chemical quality of the insulating oil, i.e. to be filtered or changed.

Effective monitoring should be done at intervals short enough to allow identification of the deterioration of insulation at an early stage. There are many factors affecting the tan delta value of the oil. These include the ageing or impurities formed during the transformer operation and the intrinsic properties of the oil itself. The cause of the increase of tan delta and its instability was found to be mainly due to the colloid formation of liquid-phobic gel. Baur describes that in theory voltage and current should be 90º shifted in phase, but in effect this does not happen as the leading reactive current is not the only current present. An active current will also be flowing and this may be caused in liquids due to three effects:
Transport of carrier (ions) through the electric field, which is also temperature dependent - with higher temperature the losses increase as a result of the ion mobility that increases with a decrease in viscosity.

The loss by rotation of electric dipoles (orientation polarisation). This may be explained as follows - a water molecule has a permanent dipole moment due to the molecular orientation. This molecule will orientate itself according to the electric field. With an alternating current the orientation of the field strength changes corresponding to the frequency of the adjacent alternating current voltage. The water molecules will shift $180^\circ$ and a loss will be incurred in the form of friction heat. With mineral oils the maximum polarisation losses are approximately at -30°C and at higher temperatures the polarisation losses decrease.

Partial discharges such as gas bubbles. Particulate quantification and identification

Both the dielectric strength and tan delta characteristics of transformer oil will be affected by particulate material. Particulate quantification and identification will assist with identification of the source of contamination. Assessing and analysing the particles present in transformer oil may detect problems, assist with the location and rectification of these, prior to the development of an incipient fault condition or seriously impaired performance of the equipment.

Background

Insulation problems involve predominantly impairment of insulation condition in service. According to Lakonin et al [6] a general ageing problem is the accumulation of conductive and polar particles in oil, as well as the deposit of these particles on the surface of the insulation material. This was noticed as adsorption of insoluble ageing products in areas of high electrical stress. The surface contamination may cause distortion of the electric field, as well as the reduction in the electrical strength of the insulation system. A typical fault that may occur is flashing over of HV windings under the effect of switching surges or lightning impulses due to contamination of surfaces with conductive particles and polar oil aging products.

Mathes and Atkins [8] reported finding that particles in oil decrease both its AC and DC breakdown voltage - the breakdown voltage being dependent on both the particle size as well as the conductivity of the particles. With conducting metal or partially conductive particles, such as carbon and wet cellulose fibers, the decrease of the breakdown strength was significantly greater for direct voltage than alternating voltage. It was recognised that small particles may agglomerate to form larger particles. These larger agglomerates may again break up under mechanical and electrical stress to form smaller particles, resulting in contradictory test results obtained in some laboratory analyses.

Sources of particles

Finnigan and Griffen [2] reported the following on a 138 kV 1964 General Electric power transformer:

During a bushing replacement on this transformer, deposits were noticed on the surfaces of the bushing that were exposed to the oil in the main tank. Two materials seemed to be the cause of the problems, corrosive sulfur and iron particles. The iron was present as iron oxides (ferric and ferrous oxides) and iron sulfides. There were probably some copper and zinc sulfides also present as was determined by the electron microscope analysis of the deposits from the bushing surface. One possible scenario for the cause of the production of the iron particles was due to mechanical stresses on the core, pressure and abrasion from vibration. The resulting iron particles formed oxides and sulfides and collected in areas of high magnetic flux.

Lewand and Griffen [3] reported the following on metals in oil:

Analysis for metals in oil is most appropriate as a diagnostic or investigative tool when other symptoms indicate an incipient-fault condition. The analysis can be performed to identify and quantify either dissolved or particulate metals in the oil, of which particulate metals are an order of magnitude less. When looking for bearing wear in pumps, a quantitative analysis for particulate copper, lead, zinc, and iron is performed. Since new oil in transformers should not have significant quantities of any dissolved or particulate metals, any appreciable increase in the oil could be an indicator of where a problem may exist. A baseline test for dissolved metals in oil is important, as the trend can be more important than the absolute quantity in identifying the location of an incipient-fault.

For transformers cooled by pumps, the test for bearing wear metals should be performed every few years. Follow up testing for dissolved metals in oil is not usually necessary unless dissolved gas-in-oil tests indicate an incipient-fault condition. The most common metals dissolved in the oil would be iron and copper or aluminum, depending on coil construction. Unusual metals such as titanium in high concentrations could come from the degradation of titanium-based paints used by some manufacturers on the interior walls of the transformer. Silicon contamination usually indicates either outside contamination (i.e. silicone fluids, caulks, or greases) or overheating of the iron components such as the core metal.

In another investigation debris was found to contain iron, titanium and silicon. The following was noted; iron was the predominant metal and could have originated from many sources such as the tank, support structures, etc. Titanium is not commonly found and suggested that the paint used to paint the inside of the transformer was the source since it was titanium-based. The silicon in the sample was probably attributable to the silicon found in the steel.

In another incident reported by Griffin [3], oil samples from affected bushings were tested and found to have some particulates, high power factor, and high moisture content. Upon investigation the particulates filtered out were found to be mostly cellulose fibers with...
some dried gasket cement. There were also some aluminum and magnetic particles.

Sokolov et al [4] reported the following service experience with twenty 500 kV sister reactor units and some 400 smaller units analysed to establish probable “weak points”. Over the period of 1976 until 1992, the failure rate was calculated to be approximately 1%. The following failure modes were noted:

- Flashover along the winding and traces of discharge on the barrier facing the winding.
- Flashover between two or more coils.
- Flashover along the inner surface of the lower bushing’s porcelain.

In several cases, severe insulation contamination consisting of metallic particles was detected. In certain cases, wearing of the bushing bearings and aluminum shield attachment were noted as sources of particle generation.

Leonardo et al [5] reported the following on oil circuit breakers.

Internal inspection on a particular unit revealed cracks and abnormal wear in the B phase interrupter shell. Interrupter shell fragments, gasket fragments and significant wear material were found in the tank. The elevated particle counts of the larger particles resulted from the deterioration of the interrupter gasket material.

Particle profiling provides important information about the deterioration of materials that result in particle production. In oil-filled circuit breakers, particle profiling can provide information about most components in contact with the oil. This includes information about in-service processes such as fluid degradation, interrupter component deterioration (e.g., baffles, arc chutes, push rods, housings, etc.), contact deterioration, mechanical wear of moving components, and rust formation. This information includes normal and abnormal contamination produced during manufacture, maintenance activities, environment exposure, fluid degradation, rust formation, interrupter component deterioration, mechanical wear of moving components, and contact deterioration.

Particle profiling can also provide information about contamination produced during manufacturing and maintenance activities as well as contamination introduced from environmental exposure.

Robles [7] reported, in a 400 kV case study, on the detection of 2 000 ppm hydrogen. Ultrasonic detection indicated heavy arcing was occurring inside the transformer. The transformer was removed from service and large amounts of conducting particles (bronze) were found inside the transformer. The particles originated from worn oil pump bearings. These particles were concentrated in high electrical field areas of the transformer and produced heavy arcing that was detected through the partial discharge emission technique.

Platts [9] reported that many samples taken from transformers contained fibers from the cellulose insulation, paper wraps on the windings and pressboard spaces. Conductive particles were of particular concern due to the reduction of the dielectric strength, the increase of the power factor and in the cellulose insulation were found to cause tracking. Fibers were routinely found in oil, but lots of fibers were found to be a problem. Sources and activities of contamination were found to be during the manufacture, maintenance activities, degradation of the cellulose insulation, or normal operation of the transformer. It was found that large particles (> 100 µm) as well as wet particles severely reduced the dielectric strength of the insulation medium. Other particles identified were, metal shavings from abrasions inside the unit, maintenance, repair work, or transformer construction, shot-blast from cleaning, varnish chips, paint chips and carbon. A bushing oil analysis indicated the presence of oil-sludge-debris. Lots of fibers and brown globules or spheres containing a white powdery substance were found. These were analysed to be copper sulphate due to reaction between copper and sulphur at an elevated temperature. The copper originated from the conductor and the sulphur from the gasket material. Zinc found was attributed to the presence of plated material in the bushing, or impurities in the copper. Aluminum originated from some aluminum components, but the silicon and iron sources were unknown. Varnish and resin were also found. In another instance molten metal found in a transformer was traced back to bushing metal due to the presence of zinc, the zinc originating from solder.

Shaffer [10] reported that certain transformer components produced specific metal particles. These metal particles may be found alone, or in different combinations and concentrations and will assist with the list of components involved in a failure. The metals found in transformers were found to be aluminum, copper, iron, lead, silver, tin and zinc. Copper was found to originate from the windings, bronze and brass components. Lead was found to be from solder joints, connectors and other peripheral components. Iron was from the windings, corona shield and ceramic bushings. Lugs, bolts, connectors and some peripheral components were found to contain tin, silver and zinc.

NTT [11] reported the following on metals and their sources; aluminum would originate from the windings, corona shields and ceramic bushings, copper from the windings, bronze and brass components. Iron would be from the core and tank, lead from solder joints, lead, tin, silver and zinc from connectors, lugs, bolts and peripheral components.

Technology for particulate analysis

The tools of choice for condition based monitoring on oil analysis, include atomic emission spectroscopy (AES) for elemental analysis and Fourier transform infrared spectroscopy (FTIR) for chemical properties. Preferred tools also include various techniques for the analysis of particles, particle counters to determine the number of particles and their size distribution, and other tools such as ferrous density and analytical ferrography to detect active wear.

Unfortunately, no single particle analysis technique is completely satisfactory in providing both qualitative and quantitative data. For example, screening techniques that use magnetism either directly or indirectly by the magnetic Hall effect can be sensitive, but are limited to ferrous materials. Analytical ferrography and filtergram techniques, while
powerful, are extremely time consuming, are subjective and require highly skilled technicians for interpretation. Conventional particle counters have proven useful for clean samples such as hydraulic fluids, but they provide no shape classification information and can run into problems with dark oils, samples with free or emulsified water droplets, or in situations where particle concentrations are high, such as heavily loaded gears or engine oil samples. Pore blockage particle counters overcome some of these difficulties, but particle shape is still unknown. Other methods have been used to quantify large wear particles including X-ray fluorescence spectroscopy (XRF), microwave or acid digestion in conjunction with emission spectroscopy (ICP or RDE) and rotodie filter spectroscopy (IFS). All of these methods make the elemental analysis of large particles possible, but they still do not provide information on a particle’s size or its morphology. A scanning electron microscope with energy dispersive X-ray (SEM-EDX) gives size, shape and elemental analysis. However, high instrument acquisition costs, along with low sample throughput, make this a costly and impractical option for most maintenance programs, except for detailed failure analysis investigations.

Particle count testing provides a determination of the number of particulates in a specific size range using the International Standards Organisation (ISO) Cleanliness code ISO 4406. An ISO code is created by selecting three ISO range numbers that correspond to the number of particles in a milliliter of fluid greater than 2.5 and 15 microns respectively.

Different types of particle counters are available, including optical, laser and mechanical filtration on a micro-sieve. The type selected has to be evaluated in terms of the application, the type of results desired and the cost effectiveness of the analysers.

Optical microscopy [12]

This technology involves the use of a compound microscope to classify particles, in terms of size and number that are collected on a membrane filter. An imprinted grid on the membrane allows the total number of particles to be estimated by statistical methods. This is generally a piece of laboratory equipment.

Image analyser system

These systems are sophisticated microscopic systems involving a microscope, a television camera, a dedicated computer and a viewing screen. Samples are prepared by filtering them through a special calibrated membrane and then the filtered particles are viewed and counted on the television screen.

Light extinction counters

These systems consist of three parts: a light source, an object cell and a photo diode, all arranged in series. The light source focuses a light beam on the object cell, illuminating its contents. The photo diode measures light intensity and produces an electrical output proportional to the degree of light extinction. Both the scattered light and the diminution of the transmitted light are a function of the particle size in the fluid. The light source is relatively inexpensive, but the equipment need to be calibrated frequently.

Laser counters

In these systems, the fluid passes through a sensor, passing a view volume area, where the laser beam is focussed. Particles in the fluid deflects bursts of light energy to a solid state diode, which converts each burst of light into pulses of electrical energy. The electrical pulses are proportional to the particle size. A digital counter sorts and counts the pulses according to their magnitude. This is a system to be used in a laboratory although portable systems are available.

Mechanical filtration counters

With this technology particle sizes and concentrations are assessed, by using the mechanical filtration characteristics of solid particles exposed to a micro-sieve. During the test fluid passes through a calibrated microsieve wafer, leaving particles on the wafer surface. As the fluid passes through the wafer, the particles will eventually block the pores of the filter, restricting the flow. The flow restriction is affected by the particle concentration and the particle size distribution in the contaminated fluid. For a given distribution of particle sizes, there is a corresponding characteristic flow rate degradation. The micro-processor using a mathematical algorithm, converts the decay curves into particle size distributions. This unit has widespread application for use in-plant as it is portable. The major drawback of this equipment is that the measurements are made on one sieve size. ISO cleanliness values of other micron sizes are mathematically calculated.

In a number of the above mentioned systems, air and water will be reflected as particles in the ISO cleanliness rating. Air bubbles can be coalesced by placing the sample in an ultrasonic bath for 30 seconds and water can be removed by a variety of dehydration techniques.

LaserNet Fines (LNF) Technology [13]

LNF is a particle shape classifier that also provides a highly accurate particle count for particles greater than 4 µm using laser imaging techniques and advanced image processing software. Silhouette images of all particles larger than 20 µm in major dimension are automatically classified into six categories:

- Cutting
- Severe sliding
- Fatigue
- Nonmetallic
- Fibers or
- Water droplets

These particles are counted by the instrument, providing a quantitative measure of active machine wear and can be viewed directly on the instrument’s computer screen. In addition to solid particles, the percent of free water is estimated based on the calculated volume of the detected water droplets greater than 20 µm while air bubbles greater than 20 µm are recognised and eliminated from the count. Concentrations are measured for particle sizes from 4 µm to 100 µm.

Methodology for particulate analysis [14]

The most widely used method for particulate analysis is the International Electrotechnical Commission (IEC) International standard
ISO 970, 1989 “Methods for counting and sizing particles in insulating liquids”. This method describes sampling procedures as well as methods for determination of particle concentration and particle size distribution.

The method makes the user aware of the fact that the particle content of a sample may be influenced by various factors. These may include the sampling point, time elapsed since filling, oil circulation flow rate and/or time elapsed since sampling (standing time), ageing condition of the oil and storage temperature.

Sampling vessels are of utmost importance. The sample containers of choice are cylindrical, flat-bottomed, wide-necked, clear glass bottles fitted with polypropylene threaded cap, forming a seal with the bottle without the use of any inserts. The volume shall be between 150 and 500 cm³.

The samples may be mixed prior to analysis by shaking in a shaker or manually, or by ultrasonic treatment.

The method of calibration is prescribed in ISO 4402 by means of air cleaned fine test dust (ACFTD).

The analysis will be reported as number of particles >2.5; >5; and >15 µm per 100 cm³ of oil. The ISO coding system is based on ISO 4406 (1999). This system reports the analysis results as an ISO cleanliness code. The three number code is based on particles ≥4; ≥6; and ≥14 µm and a scale number relating to the number of particles that may be obtained in ISO 4406 (1999).

The effect of particles on transformer dielectric strength has been studied by Working group 17 of Study Committee 12 of the IEC. They recommended some acceptable particle contamination levels as well as action that may be recommended if unacceptable levels of contamination is detected. This is summarised in Table 1.

It can be seen from the above that it was necessary to include this parameter into NRS 079-1: Mineral insulating oils (uninhibited); purchase, management and test. Not only does it make the user aware if the effects of particles, but recommended action is also included for remediation in order to avoid catastrophic failures.

Acknowledgement:

Pictures courtesy of ABB PowerTech

References

[2] Eileen Finnan And Paul Griffin, Case Studies From The Doble Materials Laboratory, Doble Engineering Company USA.
[3] Lance R Lewand And Paul J Griffin, The Effective Use Of Laboratory Analysis Of Insulating Oils As A Maintenance Tool, Doble Engineering Company USA.

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