Consequences of State of the Art Transformer Condition Assessment.

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Abstract—*The lack of the transformer community to accept the fact that transformers are chemical reactors that follow the laws of both physics and chemistry has lead to the creation of many misunderstandings with regards to transformer condition assessment and also is the reason why understanding the corrosive sulfur problem has taken such a long time.*

This paper is reports the results of an condition assessment made on a population of 30 GSU owned by a major power producer.

Keywords- dissolved oxidation products, turbidity, cleanliness, antioxidant, DBDS, relative humidity, copper content.s)

I. Introduction

The chemical reaction rate was described by Svante Arrhenius in 1898 by the equation:

$d[C]/dt= A*e^{(-Ea/RT)}$

Where d[C]/dt is the concentration change by time of chemical species.

A is a statistical parameter (chance for collision between reactants).

R is the universal gas constant.

T is the absolute temperature.

$\mathbf{E_a}$**,** (Activation Energy) was a concept introduced by Arrhenius to explain e.g. why catalysts had such a profound effect on chemical reaction rate and can be defined as follows: "The energy barrier over which a reaction system must progress in order for reactants to form products".

Thus it is imperative to assess the chemical aspects which relate to Activation energy. Any parameter which e.g. decrease the activation energy also has the negative effect of increasing the aging rate of the transformer.

Consequently, analytical work must contain relevant data for identifying these reaction parameters.

In reality and traditionally, the work of labs are basically to document the decay of the transformers rather than to discover accelerated aging and to issue warnings and recommendations on how to slow down or halt these processes.

Thus the programs applied by most labs include parameters like Total Acid Number (TAN), while antioxidant content, which prevents the formation of these acids are not commonly in use.

Also, very few labs determine the pH of these acids and some claim that the reason for this neglectfulness is due to the fact that pH for oils is an un-defined property. However, this is also the case for TAN which has been measured by labs for almost a century.

Another example is copper content in oil. A systematic investigation of copper content in oil reveal that this is a major problem. Copper is a very powerful oxidation catalyst that has been in commercial use since 1925 in petro- related chemical manufacture e.g. conversion of methane to methanol.

Instead of measuring the copper content and revealing the problem of copper (oxidation) corrosion the industry have determined tan δ (based on the Schering-bridge) and thus failed to discover why tan δ is increasing.

It is apparent that a more pro-active approach will give information that may prevent surprises to a transformer owner.

The analytical program used in this investigation comprise traditional parameters plus a large number of parameters which are normally not used. Some of these parameters are not standardized but are instead generally accepted chemical methods that have been adjusted to the use of modern analytical instruments/methods.

Antioxidant content, DBDS content, Total Acid Number + pH, Copper content, tan δ, Olefin bond content, GC-FID "fingerprinting", Density, Refractive index, GC-ECD "fingerprinting", Peroxides, Interface tension, Moisture content, Relative humidity, Dissolved oxidation products, Turbidity, DGA (precision type and including COS), Furfurals, Mercaptan Sulfur, Sulfur + Chlorine (ICP), Cleanliness (gravimetric).

The basic idea is to establish what to expect from a certain oil product and then relate what is the actual condition to the expected condition, the discrepancy being the measure of the transformer condition.

Consequently it is of great interest to categorize the oils found in the transformers.

II. The Transformer Population.

The owner selected 30 transformers to participate in this investigation. They had all been part of the monitoring program defined and performed by a major national manufacturer. The purpose of the investigation was to try to establish expected remaining lifetime and to assess the possibility of introducing pro-active maintenance as opposed to the prevailing maintenance methodology within the power producing business.

The transformers varied in age and size from 1948 to 1992 and from 15 to 350 MVA and the outcome of the investigation presented a number of unexpected facts.

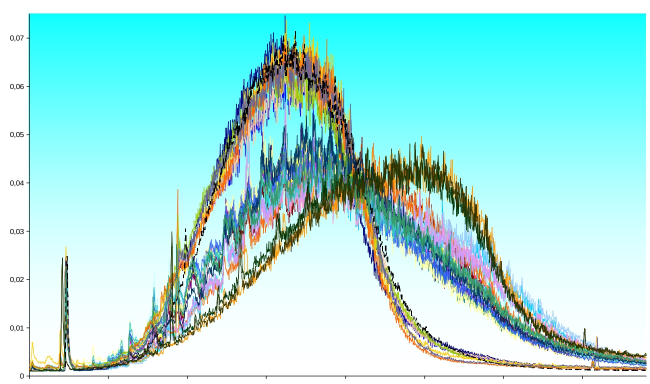
III. Determination of oil type.

It was found that basically 4 different oils were used. Out of these one was easy to identify as it was produced by one single refinery. The remainder is believed to come from several manufacturers with access to several refineries and thus the manufacturing parameters and the crudes vary to much to make possible identification (wide specification apply to insulating oils also allow this).

Property	Type 1	Type 2	Type 3	Type 4
Density.	886.8	878.1	877.0	883.1
Refr. Index	1.4764	1.4737	1.4749	1.4779
Sulfur	1120	1120	1760	1360
DBDS	17	< 0.5	< 0.5	< 0.5
Olefin bonds	112	344	102	358
Transformer age range	Avg 1980 (1948-92)	Avg 1962 (1958-74)	Avg 1963 (1948-80)	Avg1969 (1964-79)

Average properties of 4 different oil types

For type 1 it was evident that the oil in the oldest transformers had been changed at some time in late 1980s or early 1990s but there were no records of that. It is likely to be the case also for some of the other transformers in the remaining oil type groups as the oils were to modern in design as compared to the age of the transformers. It is not expected that a 1948 model transformer should contain an oil launched in 1988.



The GC-fingerprints show four different oils.

It is also of interest to note that the copper corrosion causing additive DBDS is found only in the most modern oils and in the most modern transformers.

Trace levels (< 2 ppm) of DBDS were found in transformers which have been subjected to antioxidant inhibitor make-up after regeneration processes have been performed due to the fact that the concentrated inhibitor solution also contained DBDS at levels around 200 mg/kg (ppm). If 1 ton of such a solution (5 barrels) is required to obtain correct oxidation protection level, 50 gram of pure reactive sulfur is added and may cause a great deal of problems.

IV. Evaluation.

It is the total condition evaluated that is of interest and in order to make possible such an evaluation it is necessary to understand the influence of some of the parameters. It is therefore appropriate to deliver a brief description of the influence of each parameter.

a. Oil type/quality descriptors.

As already shown: the GC-chromatographic fingerprint, density, sulfur content and refractive index give information about which base oil type and degree of oil refining. Olefin bonds content give information on the degree of base oil saturation.

Natural base oils are always completely saturated (<10 ppm) but todays oils are always cracked and saturation is expensive and not required in the international standards so it is therefore a parameter not highlighted by manufacturers. A saturated oil give very good long term performance.

The level of olefin bonds increase as the oil is in operation and the rate of change is a very good descriptor of fault or aging development in the transformer.

b. Inhibitors.

The content of antioxidants indicates how well the transformer is protected against its greatest enemy: the oxygen ingested during operation.

Two basic types of antioxidants have been found to be in use: phenolic types (e.g. BHT, E321) and di-sulfide types.

Di-sulfides seem to have been in use for a very long time and have been labeled “natural antioxidants” and used in oil which are required not to contain antioxidants. Due to the numerous failures that have been reported to have appeared some oil companies have discontinued the use of this additive. The additive is harmless unless it is subjected to high temperatures and presence of catalytic metals such as copper. High temperatures are not present in old designs and this additive performed its service as antioxidant well. Transformer failure indicate the existence of local very high winding temperatures which this additive is not intended for

BHT is excellent to prevent cellulose and oil ageing and thus prevent the parameters developing as a consequence of aging (e.g. Total Acid Number).

c. Ageing promoting parameters.

There are a number of factors which accelerate aging. The tendency for aging is an auto-catalytic behavior i.e aging products have a tendency to increase aging and it is therefore essential to maintain "as-new" conditions as long as possible. The standard behavior of determining Total Acid Number (TAN) only determine the development along ONE aging path and is also a method of documenting the decay and not managing the life preserving parameters.

Moisture is formed mainly due to the degradation of cellulose but also due to the degradation of oil. Contrary to what many believe, moisture has only an indirect effect on aging as it provides a transportation means for the very water soluble **peroxides** which degrade the cellulose.

Relative humidity or water activity (= correct chemical term a_w) are now available and recommendable methods for correct and easy assessment of this parameter.

Peroxides have been determined systematically since 1999 by **VP**diagnose and a new type of faults was early discovered (extremely high peroxide number > 50 mg/kg as H_2O_2).

Copper is a very strong oxidation catalyst both in its metallic and in its corroded (oxidation corrosion) metal organic oil soluble form. **Tan δ** correlate closely to copper content in oil but tan d also correlate to other metal organic and polar type of compounds. Experience since 1996 have shown that in >99% of the cases, metal-organic copper is the reason for elevated tanδ.

Carbonyle sulfide (COS) is detected by DGA and its presence indicate copper corrosion conditions.

Mercaptane sulfur (as H_2S) is found in new oils but only in very low levels in used oils. Its occurance in transformers increase by time but its extreme reactivity make it very difficult to assess/interpret.

Chlorine has been found to promote corrosion on copper conductors surfaces. This corrosion effect is often misinterpreted as corrosive sulfur by the CCD-method launched not long ago.

It was a big mistake to accept a method which is based a) on a chemical process where the chemical processes are not thoroughly researched b) where an ocular inspection is made and the reason for corrosion can be misinterpreted.

DBDS and **GC-ECD fingerprinting**: DBDS is the compound that has given rise to the world wide problem of corrosive sulfur. This type of compounds has been used as double acting additive in lubricants: peroxide terminating antioxidant at low temperatures and very strongly acting anti wear additive at elevated temperatures due to its immediate triggering at a well defined temperature and to the extreme rate of reaction it forms a protective sulfide layer on metal surfaces. When this layer is not wanted; it is labeled corrosive.

Copper in any form and of high specific surface area is catalytic and degrades the insulation system.

pH indicate if the acids found in the TAN-determination are strong or weak. Strong acids give corrosion and corrosion will give increased surface areas of corrosive agents. It is also known that corrosion indications by pH also indicate localized corrosion.

For used oils the **olefin bonds** content is of interest as olefin bonds adhere to copper surfaces and enable reactions to take place. An oil without these weak parts of the molecules will not age at all unless subjected to very strong chemical provocations. Also the antioxidant protection of such an oil is extremely strong.

d. Aging products.

Aging has many possibles reaction paths and therefore the level of aging cannot be described by one parameter only.

Water and CO_2 are the final products formed by cellulose and oil when degradation by oxidation reactions. Thus moisture, CO and CO_2 indicate insulation system degradation.

Oil degradation is traced by **TAN**, **interface tension**, **dissolved oxidation products**, **turbidity**, **oil cleanliness** (gravimetric) and in the **GC-fingerprint**.

Dissolved oxidation products and turbidity have proven to be of great value, especially for transformer oils which have been regenerated as these oils are normally tested only by the classical, ancient methods. The methods in combination will during follow-up diagnostics catch any transformer having been exposed to insufficient quality regeneration process.

Furfurals has been used for many years to attempt to asses the cellulose condition but with very limited success. In this investigation it was included on the clients request. Cellulose degradation is more readily assessed by combining data but basically asses carbon oxides.

e. Fault Detection.

Rapidly developing faults are assessed by DGA while long term faults are assessed by a the remaining analyses in combination with DGA. For earliest possible detection, high precision DGA is recommendable despite high productivity screening methods are now prevailing (GC-Head Space).

High precision DGA involves extraction of the gases in combination with using actual oil density instead of assumed oil density.

Round Robin tests of Head Space type of DGA always give very good results mainly because only new oils are used in the Round Robin samples and in combination with the fact that the calibration is performed based on new oil indicate good results. However, the real samples are always used oils and therefore the calibration is erroneous.

V. Transformer Condition Assessment Results.

Not very surprising, older units revealed strong oxidation because they had been without antioxidant protection for a very long time.

However, newer designs showed proportionally higher degree of oxidation, probably due to the higher thermal load that the insulation system is subjected to in newer transformers.

This also did show in the copper in oil content. Some old transformers had very low copper content while the newer the transformer the higher the level detected. A number of transformers had levels that indicate that the cellulose insulating capacity was decreasing and therefore tan d of the transformer was strongly recommended.

Performing such measurements in the frequency domain will give valuable information on the cellulose insulating parameters condition.

Of the relatively large part of the population which had been subjected to regeneration it was found that 25 % had had insufficient regeneration process and turbidity and dissolved oxidation products were already high. A number of these units also consumed antioxidants at a very high rate indicating bad operating conditions (e.g. insufficient cooling) or slowly developing faults.

It was also evident that (any) transformer owner has a tendency to relax when the transformer oil has been regenerated and to forget that maintenance is required also in the future.

The interpretation of the necessity to regenerate the oil of a transformer is that a) insufficient maintenance practices led to the expense, or b) bad operating parameters aged the oil prematurely, or c) the intrinsic stability of the oil was to low (olefins i.e. cheap or low quality oil).

DBDS was found to be a problem with only one of the four oil types and the newer the transformer the higher the content of DBDS. As DBDS turns into a problem at a well defined energy level (basically a well defined temperature) it is quite clear that the dangers of DBDS-presence cannot be easily assessed without access to a large data base or trustworthy transformer manufacturer data.

DBDS has been in use since mid 1960s and was not a problem until late 1980s.

Old transformers are not sensitive i.e. DBDS act in antioxidant function.

Newer transformers are, since mid 1980s, designed according to “average winding temperature rise 65 K” as opposed to 55 K in earlier power rating definition. Therefore these units have a very much more severe chemical situation where some transformer designs locally (in the upper parts of the winding) operate above the trigger temperature for DBDS in its anti wear function.

VI. Consequences of the Condition Assessment.

The owner is:

- Launching a program of electrical assessment of units found to be in dubious or bad condition.
- Launching a program of pro-active maintenance according to the condition assessment outcome. This includes active measures against DBDS but exclude the use of copper passivators as it is found to be ineffectual.
- Launching a program of transformer life-time extension to decrease long term costs.
- Now well aware that the remaining life time of an old transformer may well be equal to or exceed that of a new transformers total life.

Life time extension is a practical means to increase transformer lifetime at very low cost. It also has the benefit of engaging the maintenance personnel more actively and thus create better understanding of how the transformers work with respect to life time.

VII. Summary.

For the 30 transformers a large number of transformer operating years have been saved. There will be an increased initial cost to start the programs but the long term savings will be very large both in money terms but also in environmental impact as fewer new transformers will be purchased annually..

For power producers with ISO 14000 certifications the life time extension aspect should be emphasized and also the expected life time of new transformers should be treated likewise.

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