

# Ageing transformers, from Liability to Reliability

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#### Abstract.

Large power transformers are critical components in the grid network.

Utilities and other transformer operators world wide, are confronted with the problem of an ageing transformer population, increasing demand and an ever-increasing incidence of failure.

As transformers age the risk of failure increases reaching exponential proportions towards the end of the transformers life. The high capital cost of replacement and the long lead times associated with manufacture mean that the risk to supply continuity is high.

Current maintenance practices and limitations with regard to the adoption and use of standards, means that most transformer failures are unexpected. The reactive nature of transformer maintenance incurs severe cost penalties for operators and a loss of reputational standing. Unexpected failure may cause injury or death, environmental hazards and loss of revenue and good will.

The assessment of a transformers condition coupled with an appropriate programme of remedial processing and ongoing condition monitoring with effective moisture management can reduce the risk of failure and maximize the useful, reliable operational of transformers.

#### Introduction.

In order to build an effective and realistic maintenance programme it is necessary to understand the current practices. Most transformer operators rely upon a combination of visual inspection, Electrical testing and oil sample analysis to assess the state of health of their transformers and whether any remedial actions are required. IEEE C57 standards recommend that transformers rated above 500kVA be electrically tested annually. In practice, it is more common to find these transformers tested at intervals between 3 to 5 years, and often this stretching to 8year intervals and in some cases these transformers are not tested at all.

The visual inspections normally done at yearly intervals are seldom done due to the decrease in manpower and budgetary restrictions.

This leaves the oil sample testing. This is typically done on an annual basis and it is upon this that we will focus as the primary source of information about the health of the transformer.

#### What do we seek to achieve?

The familiar "bathtub curve" illustrates the typical life cycle of most components.

Our goal is to maximize the "useful operational life" portion of the curve.

Most analyses tend to identify conditions in a transformer at the onset of the "old age" and consequently closer to the end of the transformer life. It is hoped that this can assist in identifying prob-

# Expected component life (Bathtub curve)



lems so as to avoid the unplanned outages associated with catastrophic transformer failure but it is often not the case. It is also not as useful as identifying the problems earlier so as to be able to take preventative actions.

It was recognized by IEEE that more than 80% of all transformer failures world wide, occur due the failure of the solid insulation. In particular the Kraft paper insulation in the windings. Of all the component parts in a transformer it is the Kraft paper insulation (cellulose) that is the most vulnerable. Once damaged, it cannot be repaired and the life of the transformer will be forever shortened. Paper life = Transformer life.

It follows then that anything we can do to prevent or mitigate damage to the paper insulation will enhance the life of the transformer.

So what limits the life of the paper insulation?

Modern insulation paper starts life with a tensile strength of around 17,500psi (120MPa). As it ages is loses its mechanical strength due to the effects of heat, moisture and contamination. The strength of the paper is referred to as the degree of polymerization, of DP. These properties are used to evaluate the end of reliable life of paper insulation. It is generally suggested that DP values of 150-250 represent the lower limits for end-of-life criteria for paper insulation; for values below 150, the paper is without mechanical strength.

Analysis of paper insulation for its DP value requires removal of a few strips of paper from suspect sites. This procedure can conveniently be carried out during transformer repairs. The results of these tests will be a deciding factor in rebuilding or scrapping a transformer.



#### **Furaldehyde Analysis**

Direct measurement of these properties is not practical for inservice transformers. However, it has been shown that the amount of 2-furaldehyde in oil (usually the most prominent component of paper decomposition) is directly related to the DP of the paper inside the transformer.

Paper in a transformer does not age uniformly and variations are expected with temperature, moisture distribution, oxygen levels and other operating conditions. The levels of 2-furaldehyde in oil relate to the average deterioration of the insulating paper. Consequently, the extent of paper deterioration resulting from a "hot spot" will be greater than indicated by levels of 2-furaldehyde in the oil.

The progression towards insulation failure.





This diagram shows how the dissolved moisture and heat act upon the paper insulation.

In work done in the 70s by F.M/Clark of General Electric in the US, he showed by experimentation in the laboratory a distinct relationship between the acid number fo the oil and the tensile strength of the paper insulation when an oil/paper sample was aged in the laboratory. SD Myers replicated these experiments in the 80s with similar results.



The effect of the oil acid level being at 0.15mgKOH/g is clear and represents a 40% loss of tensile strength.



The following two photomicrographs were taken of "new oil" on the left and "aged oil" on the right, using a scanning electron microscope and at 750 x magnification.

The oxidation decay products found in transformer oil will continue to attack the paper insulation as longs at they remain in contact with the paper.

In order to minimize the damage to the paper insulation we need to:-

1. Identify the indicators contained in the oil analysis that indicate deterioration.

2. Redefine the levels at which we need to take action when these are observed in analysis results.

3. Take appropriate remedial action in a timely manner.

#### The gaps in current analytical practice.

Current analytical practice relays upon standards such as IEC60422 - 2005 for guidance on what to test for and at what levels these should be classified as problematic.

The biggest problem in this is that the standards are designed in terms of analyzing the oil for its characteristics as *a dielectric me-dium* with little attention to the effects on the paper insulation.

It is for this reason that it is necessary to look at the analysis and to use a more appropriate form of classification of the oil characteristics so as to be able to take the appropriate and timely action.

There are no standards in existence that define this for us but there has been much work done by both SD Myers and DOBLE in this area and a system of classification that allows us to identify the conditions and to be able to plan the remedial actions can be drawn form this and from practical experience.

#### When to act?

Waiting until known harmful conditions reach "limits" is both damaging and dangerous.

For this reason and with the maximization of the paper insulation in mind, the following grading system may be adopted.

ACceptable, QUestionable and UNacceptable, e.g. AC, QU, UN. Based upon the known standards, accepted norms and experience.

Once adopted, the characteristics defined in this manner gives us; a) the ability to recognize a damaging condition developing and b) the time to effectively plan appropriate remedial action.

**AC**cceptable = within the safe operating range and requires only continued monitoring.

**QU**estionable = Parameter is now showing signs of deterioration and remedial action should be planned

**UN**acceptable = Parameter is now causing damage to insulation system and urgent attention is required.

The guides given in the following tables are based upon classification of the transformers by Voltage in accordance with IEC 60422 of 2005.

For the purposes of monitoring oil condition the key characteristics are:-



#### Moisture content.

Not just the amount of moisture contained in the oil and expressed in ppm but the more importantly:-

• The saturation level of the insulating fluid.

• The amount of moisture trapped in the paper insulation (expressed as the percentage Moisture by dry weight or %M/dw)

#### Saturation level of the insulating fluid.

Moisture is not very soluble in new, clean transformer oil. The solubility of water in oil is higher at higher temperatures. Comparing how much moisture is dissolved in the oil to how much moisture the oil can hold is what is known as the relative saturation of the oil. For example, new, clean oil at 40 Deg C will hold little more than 120ppm of moisture in solution. If the actual moisture content at 40 Deg C is 12ppm then the relative saturation will be 10%. If the moisture in the oil is higher than the desired relative saturation and the transformer should cool significantly, some of the dissolved moisture can come out of solution as droplets of free water. These could cause immediate dielectric failure if they came into contact with an energised conductor.

% Saturation guide.

Voltage class	AC	QU	UN
<72.5 kV	<15%	15 – 20%	>20%
72.5 – 170kV	<8%	8 – 12%	>12%
>170kV	<5%	5 – 7%	>7%

#### Moisture by Dry Weight (M/dw)

Moisture in the paper insulation is of concern primarily because it causes the insulation to age prematurely, shortening the useful life of the transformer. At high enough levels of moisture in the paper flashover can occur at temperatures encountered in the normal operation of the unit. It is more useful to grade %M/dw results as in the table below than simply as AC, QU and UN.

The upper end of the "A" category (1.25%) represents the maximum %M/dw where accelerated ageing of the insulating paper has not yet begun. As the %M/dw increases from this point, it becomes progressively more difficult (and thus more time consuming and costly) to address.

#### Neutralisation Number (acidity).

The level of acidity is an indication of the oxidation level of the transformer oil and is normally determined by means of adding an Alkali (Potassium Hydroxide, KOH) to a sample of the oil so as to "neutralise" the acid content (hence the term Neutralisation Number). As the oxidation level of the oil increases polar compounds and particularly organic acids form in the oil. These react with the other materials in the transformer and ultimately form sludge, which deposits on the surface of the paper insulation preventing the proper cooling of the windings and accelerating the decay of the paper insulation. These acids also cause corrosion within the transformer.

#### **Interfacial Tension (IFT)**

The IFT of the oil is a very good early warning indicator of the build up of polar compounds in the transformer oil. These polar compounds (particularly the acids) are the precursors to sludge as described in the previous paragraph. The IFT is a very good indicator of sludge conditions.

#### Neutralisation number (Acidity) and Interfacial tension (IFT) guide

	AC	QU	UN
Acidity mgKOH/g	<0.05	0.05 – 0.10	>0.10
IFT mN/m	>30	32 – 22	<22

# Dielectric Dissipation Factor – DDF (Liquid power factor or Tan $\delta).$

DDF is an outstanding tool for evaluating in-service transformer oil. The test is valuable for acceptance testing of new oil from a supplier, and for evaluating conditions in newly installed equipment. For in-service oil, there are several adverse conditions that show up as changes in the liquid power factor results.

New, clean, and dry transformer oil starts out with a very low liquid power factor, typically <0.003% at 90 Deg C.

As the oil ages or becomes contaminated, the liquid power factor

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Voltage class	A	В	С	D	E
<72.5 kV	0 - 1.25%	1.25-2.00%	2.01-2.5%	2.51-4.0%	> 4%
72.5 – 170kV	0 – 0.85%	0.86 – 1.35%	1.36 – 1.70%	1.71 – 2.65%	>2.65%
>170kV	0 -0.55%	0.56 - 0.85%	0.86 - 1.05%	1.06 - 1.70%	>1.70%

% Moisture by Dry weight guide (M/dw)

A – The highest level of moisture before accelerated ageing begins

D - The highest level of moisture where cost effective removal is possible.

A:	Acceptable, normal operation.		
B:	Best time to remove excess moisture		
C:	Wet, must address problem.		
D:	Last chance, may already be too late.		
F:	Disaster waiting to happen.		

increases. Liquid power factor is usually run in the laboratory at two temperatures, 25 Deg C and 90 Deg C each temperature provides unique direction in what is happening with the fluid. If an abnormal value for liquid power factor is obtained during testing, the respective trends of these two values over the past history may be used to help diagnose the conditions that may be causing the abnormal values.

The concept behind the test is quite straight forward. When an insulating liquid such as transformer oil is subjected to an alternating current field, the oil experiences dielectric losses. These losses cause two effects. The resulting current is deflected slightly out of phase with the AC field that has been applied, and the energy



of the losses is dissipated as heat. Liquid power factor (dielectric dissipation factor, or a closely related measurement Liquid Power Factor, which is similarly interpreted) is calculated from direct measurement of these dielectric losses, the lower these losses, the better the oil condition.

Dielectric Dissipation Factor is the tangent of the loss angle while Liquid power factor is calculated as the sine of the same loss angle – the amount of current deflection due to dielectric loss. Some test standards refer to the dissipation factor as tan  $\delta$  because the loss angle is designated as  $\delta$  in the vector diagram. Values may be expressed as either a decimal number or as a percentage, such as 0.001 or 0.10%. Typically, in the management of electrical equipment and insulating oils where these dielectric losses are very low, we use values for direct measurement of the DDF.

Note that the calculated values for liquid power factor and for dissipation do not differ by very much until you get into the larger decimal values for each. At a calculated liquid power factor (four significant figures) of 10.00%, the dissipation factor would be 10.05%.

Contamination of the oil by moisture or by other contaminants will increase the liquid power factor. The aging and oxidation of the oil will also elevate liquid power factor values. Therefore, this is an extremely useful test because almost everything "bad" that can happen to the insulating oil will cause the liquid power factor to increase. Running the test at two temperatures allows for some further diagnostics concerning the cause(s) of the abnormal power factor.

	AC	QU	UN
@ 90 Deg C	< 0.02	0.02 – 0.05	>0.05
	<(2%)	(2% - 5%)	>(5%)

#### **Oil Quality Index Number**

Dividing the IFT (Interfacial Tension) by the Neutralisation Number (NN or Acidity) provides a numerical value that is an excellent means of evaluating oil condition. This number is known as the Oil Quality Index Number OQIN. A new oil would have a OQIN of 1500.

#### What remedial action is appropriate?

Depending upon what conditions are identified by the analysis, the level of contamination and the condition of the paper insulation there are a number of remedial actions available to us.

1. Energised transformer oil regeneration (also called reclamation).

The energized regeneration of transformer oil is a well-established and highly successful technique for the restoration of degraded mineral insulating oils to a fully healthy condition.

In addition, when correctly performed, it will remove accumulated sludges and other contaminants from the solid (cellulosic – including the winding insulation paper) insulation.

It is however essential that the process and the governing factors are fully understood and carried out by a knowledgeable and experienced operation.

2. Energised transformer oil purification.

This technique gives us the ability to remove, moisture, gases and particulate matter from the transformer in the energised condition.

3. Transformer oil purification (de-energised condition)

This technique, essentially the same as 2 above, but is carried out on the transformer oil with the transformer de-energised. This may be required when the moisture content of the

OQIN	=	IFT
		NN

1500=45.0(typical new oil) 0.03(typical new oil)

## TRANSFORMER OIL CLASSIFICATIONS

1. GOOD OILS NN – 0.00 – 0.1 mgKOH/gm

IFT - 30 – 45 mN/m

Colour - Pale yellow

OQIN - 300 - 1500

2. Proposition "A" oils NN – 0.05 – 0.10 mgKOH/gm

IFT - 27.1 – 29.9 mN/m

Colour - yellow

OQIN – 271 - 600

 Marginal oils NN – 0.11 – 0.15 mgKOH/gm

IFT - 24 - 27 mN/m

Colour – Bright yellow

OQIN - 160 - 318

4. Bad oils NN – 0.16 – 0.4 mgKOH/gm

IFT - 18 – 23.9 mN/m

Colour – Amber

OQIN - 45 - 159

5. Very bad oils NN – 0.41 – 0.65 mgKOH/gm

IFT - 14 – 17.9 mN/m

Colour – Brown

OQIN - 22 - 44

#### Conclusions

By reviewing the way analysis is performed and when a sound understanding of the condition of the paper insulation can be determined. It is possible that by adopting appropriate remedial actions / techniques. The factors and conditions that negatively effect transformer life can be mitigated.

This leads to a reduction in the risk of failure and the extension of the life of these expensive and critical assets, allowing for the proper planning / budgeting of action and often the deferment of capital expenditure.