TECHNICAL BULLETIN

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TALKING TRANSFORMER TESTING

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INTRODUCTION

Condition monitoring is the frequent collecting, measuring, recording, and analysis of the relevant data regarding an asset's operation. If we interpret the data correctly, it can give us great insight into the asset's condition.

Frequent monitoring of the asset can result in less maintenance required or more extended periods without any maintenance required.

It is crucial to identify the key parameters that are needed to give us a complete picture of the actual status of the transformer and the action we need to take to ensure the continued reliability of the asset to achieve the maximum lifetime.

WHAT IS THE DATA TELLING US?

- Has the condition of the unit changed since the last maintenance period?
- Is it safe to operate the unit?
- Are there signs of deterioration?
- Is it safe to load the unit above the nameplate rating for a particular period?
- Are we required to implement action to ensure the continued reliability of the unit?
- How long can we use the unit before we need to consider replacement?
- Are the identified problems of a recurring nature?

EFFECTIVE CONDITION MONITORING OUTLINE

It is vitally important to identify clear goals as part of your strategy. What do you want to achieve by implementing this condition monitoring plan? Is it in-service failure prevention? Or maybe life extension? Maintenance deferral? By stipulating the outcome and what you want to accomplish, it would be much easier to identify the required parameters.

Health indexing of assets is becoming a remarkable tool in getting a clearer picture of the condition of your transformer. Test parameters carry a numerical value-adding to the total value of the Health Index Value of the transformer. These parameter weight values were calculated based on the international standards for mineral oils, indicating the critical values stipulated in the various standards.

THE SCOPE OF OIL ANALYSIS, INTERPRETATION OF THE DATA, AND CRITICAL VALUES

At the beginning of this section, it is essential to state that we deal with different size transformers in the industry. Transformers are divided into classes according to the kV ratings of the equipment. It is up to the reliability or asset manager to use the guidelines for larger equipment, thereby implementing shorter increment oil analysis and electrical tests.

The maintenance engineer or manager needs to determine what type of testing would benefit him in identifying problem areas within his fleet. Some of the analysis has been identified as to routine type tests. Still, there is an extensive range of tests that can assist in identifying specific problem criteria within the system, which might not be clear through the typical day-to-day analysis usually performed.

Please see the rating classes in TABLE 1

TABLE 1 - CATEGORIES OF EQUIPMENT

CATEGORY	TYPE OF EQUIPMENT
Category O	Power transformers/reactors with a nominal system voltage of 400kV and above
Category A	Power transformers/ reactors with a nominal system voltage above 170kV and below 400kV. Also power transformers of any rated voltage where continuity of supply is vital and similar equipment for special applications operating under onerous conditions.
Category B	Power transformers/reactors with a nominal system voltage above 72.5kV and up to and including 170kV (other than those in Category A)
Category C	Power transformers/reactors for MV/LV application e.g. nominal system voltages up to and including 72.5 kV and traction transformers (other than those in Category A). Oil-filled circuit breakers with a nominal system voltage exceeding 72.5kV. Oil-filled switches, a.c. metal-enclosed switchgear and control gear with a nominal system voltage greater than or equal to 16kV
Category D	Instrument/protection transformers with a nominal system voltage above 170kV
Category E	Instrument/protection transformers with a nominal system voltage up to and including 170kV
Category F	Diverter tanks of on-load tap-changers, including combined selector/diverter tanks.
Category G	Oil-filled circuit breakers with a nominal system voltage up to and including 72.5kV Oil-filled switches, a.c. metal-enclosed switchgear and control gear with a nominal system voltage less than 16kV

NOTE 1 Separated selector tanks of on-load tap-changers belong to the same category as the associated transformer
NOTE 2 Oil-impregnated paper bushings and other hermetically sealed equipment may be placed in Category D or E if a routine monitoring programme is desired. The manufacturer's instructions should be referred to.
NOTE 3 Regardless of size or voltage, a risk assessment may justify condition-monitoring techniques usually appropriate to a higher classification.
NOTE 4 For practical and economical reasons, some electrical utilities may decide that their small transformers up to 1 MVA and 36kV are not included in this classification. Routine monitoring may not be considered economical for this type of equipment. Where a monitoring programme is required for these transformers, the guidelines in category C should be adequate.

TABLE 2 explains which oil analyses are recommended and how often or under which circumstances.

TABLE 2 - TESTS FOR IN-SERVICE MINERAL INSULATING OILS			
Property	**Group**	**Subclause**	**Method**
Colour and appearance	1	5,2	ISO 2049
Breakdown voltage	1	5,3	IEC 60156
Water content	1	5,4	IEC 60814
Acidity (Neutralization Value)	1	5,5	IEC 62021-1 or IEC 62021-2
Dielectric dissipation factor (DDF) and resistivity	1	5,6	IEC 60247
Inhibitor content [b]	1	5.7.3	IEC 60666
Sediment Sludge	2	5,8	Annex C of this standard
Interfacial tension (IFT) [c]	2	5,9	ASTM D971 EN14210
Particles (counting and sizing) [c]	2	5,1	IEC 60970
Oxidation stability [c]	3	5,7	IEC 61125
Flash point[d]	3	5,11	ISO 2719
Compatibility[d]	3	5,12	IEC 61125
Pour point[d]	3	5,13	ISO 3016
Density[d]	3	5,14	ISO 3675
Viscosity[d]	3	5,15	ISO 3104
Polychlorinated biphenyls (PCBs)	3	5,16	IEC 61619
Corrosive sulphur[c]	3	5,17	IEC 62535 ASTM D1275, METHOD B DIN 51353
Dibenzyl disulfide (DBDS) content	3	5,18	IEC 62697-1
Passivator content[b]	3	5,19	ANNEX B OF IEC 60666:2010

[α] Group 1 are routine tests, Group 2 are complementary tests, Group 3 are special investigative tests
[b] Restricted to inhibited and or passivated oils.
[c] Only needed under special circumstances, see applicable subclause.
[d] Not essential, but can be used to establish type identification.

OIL SAMPLING

The taking of the oil sample is one of the most crucial and critical influencers in the analysis outcome. If a sample is not taken to the prescribed procedure, then there is a significant possibility that the analysis performed, and the results acquired, are of no use.

Care should be taken to ensure quality control procedures are applied in each step of the sampling process as set out by international standards. A good quality sample taken by applying the correct procedure is essential. A sample can be contaminated by various factors, all of which can influence the outcome of the results in a negative manner.

All steps involved in sample taking must adhere to quality control procedures, including the container that is used, the sampling kit, the taking of the sample, the marking of the sample, the closing of the sample, the storage and handling of the sample, and then the delivery of the sample to the laboratory.

If the sample identification and sample data are handwritten, the human factor can lead to incorrect interpretation of the data. The label should be stuck onto the container to ensure no mix-ups in sample identification. Ensure that the label is completed in neat, easy-to-read handwriting. The label should be waterproof, and the pen used to write on the label should be oil- and water-resistant. Otherwise, some data might be lost, making it extremely difficult for the laboratory personnel to complete the report or allocate the sample to a specific transformer.

Now, let's discuss the types of tests to determine the transformer's condition, the critical values, and the recommended actions in each case:

a) Colour and appearance

This is a routine inspection applied to every oil sample.

When an oil sample arrives at the laboratory, one of the "tests" is a visual inspection of the oil sample in a clear vessel to determine the colour, turbidity, and possible particle identification.

Dark oils might indicate chemical degradation or contamination of the oil.

When there is a lot of turbidity, it might indicate a high water content in the oil.

If the drain valve was not wiped clean by the sampler, the dirt particles in the drain valve might be incorporated into the sample. If particles are identified as carbon, it might indicate a possible electrical fault in the unit. The DGA analysis of the oil will confirm if this is the case.

Clear oils without contamination will indicate a good condition, and no action is recommended.

When oils are dark or turbid, further analysis will confirm any problems. The oil analysis results will also determine the degree and type of action.

b) Breakdown Voltage

This is a routine inspection.

Property	Category	Good	Fair	Poor
Breakdown Voltage (kV)	O, A, D	>60	50 to 60	<50
	B, E	>50	40 to 50	<40
	C	>40	30 to 40	<30
	F	<30 kV for OLTC in star point application <40 kV for OLTC in delta or line-end application		
	G			<30

Breakdown voltage will indicate the water content or the presence of foreign particles, or both in the oil being analysed.

As the oil in transformers acts as an insulation medium to avoid flashover in the unit, the breakdown voltage must be high.

If the values are **Good**, it is recommended to continue with the current sample interval action plan.

If the values are **Fair**, more frequent sampling is recommended in collaboration with other parameter results like the water content, DDF (dielectric dissipation factor), and acidity.

If values are **Poor** – it is recommended to recondition the oil via oil reconditioning processes. If alternative tests indicate severe aging, the oil can be replaced with new or reclaimed oil. Another option would be to perform on-site oil reclamation using a reclamation plant.

Reclamation of oil has the advantage that the colour of the oil is restored, and the polar components are removed from the oil. This process removes acid and water as well as some other compounds. Another advantage is that the oil can be re-used, and in most situations, this can be done without switching off the unit, which contributes to cost-saving. If in doubt – instead switch off the unit during this treatment process.

If the values are **Poor**, it is advisable to take action as soon as possible and not delay the maintenance process. Excess water in the transformer system decreases the projected transformer lifetime significantly; extremely high water content can cause flashover in the unit, resulting in loss of the asset.

c) Water content (mg/kg at transformer operating temperature)

Property	Category	Good	Fair	Poor
Water Content (mg/kg at Transformer Operating Temperature)	O, A	<15	15 to 20	>20
	B, D	<20	20 to 30	>30
	C, E	<30	30 to 40	>40
	F	Action necessity >40		
	G	Not a routine test		

This is a routine test for all classes of electrical equipment, except class G.

The results of this test should always be considered in conjunction with the breakdown strength. If it is found that the water content is high and the breakdown strength is low, further action needs to be taken. It is recommended that a second sample from the same unit is tested to confirm the results.

In the case of switching equipment, where there is no paper present, the breakdown voltage is the determining factor.

It should be noted that the limits indicated by IEC 60422 Edition 4 apply to transformers with operating temperatures between 40 and 70 °C. If it is found that the unit's operating temperature is outside this temperature range, it is best to refer to Annex A of the standard.

When the value obtained through analyses is **GOOD**, the normal sampling interval can be maintained, requiring no further action.

When the value returns a **FAIR** result, more frequent sampling is recommended. It is also helpful to consider other parameters like the breakdown voltage, particle content and DDF/resistivity, and acidity to decide on the action to be implemented.

A **POOR** result will require immediate action from the asset manager. This might include taking another sample to confirm the results from the first analysis. If it is confirmed that the water content is high, the oil can be filtered; this process should remove a large portion of the moisture from the oil if applied correctly. Follow-up samples need to be taken to ensure that the moisture content is still within the required limits. The reason is that the most significant portion of the water is caught up in the paper system in the transformer. This moisture will move from the paper into the oil under conditions that favour this movement. It might be found later that the oil in the water has increased again without any apparent reason, but the source would be the paper in the transformer.

A visual inspection is also recommended to determine if any water might move into the transformer or electrical equipment through leaks. This problem might be more severe if the transformer or electrical equipment is outside and not in a covered area.

d) Acidity (mgKOH/g oil) Neutralization Number

This is a routine test for all classes except F and G.

The acids in oils are formed due to chemical reactions between the oil, water, and paper. Higher temperatures or load increases will assist in the formation of the acids. Because acids are polar compounds, it will adversely affect the insulation properties of the oil and will increase paper degradation. If left untreated in transformers, this can lead to sludge formation, usually around the lower parts of the transformer core. The sludge will eventually form a semi-solid substance that is extremely difficult to remove.

Property	Category	Good	Fair	Poor
Acidity mgKOH/g oil	O, A, D	<0.10	0.10 to 0.15	>0.15
	B, E	<0.10	0.10 to 0.25	>0.20
	C	<0.10	0.15 to 0.30	>0.30
	F, G	Not a routine test		

If the result is **GOOD**, the regular sampling interval can continue.

In case of a **FAIR** result, the sampling interval should be decreased to fit the situation. Future analysis should include a visual inspection of the oil for sediment and sludge.

If the result is **POOR** according to the prescribed values in IEC 60422 Edition 4.0, the asset manager may decide to reclaim the oil or replace it with new or reclaimed oil, whichever option might suit their requirements the best.

e) Dielectric Dissipation factor at 40Hz to 60Hz at 90° C

Property	Category	Good	Fair	Poor
Dielectric Dissipation factor At 40Hz to 60Hz at 90°C	O, A	<0.10	0.10 to 0.20	>0.20
	B, C	<0.10	0.10 to 0.50	>0.50
	D	<0.01	0.01 to 0.03	>0.03
	E	<0.10	0.1 to 0.3	>0.3
	F, G	Not a routine test		

This is a routine test for all classes of electrical equipment, except F and G.

The dielectric dissipation factor or tan delta of this test provides information regarding the extent of the dielectric losses in transformer oil. This test measures the inefficiency of insulating material.

When oil ages, we have the formation of polar compounds, leading to phase displacement and dielectric losses. Other impurities that might influence the dissipation factor include water, dissolved insulating resin, and paper.

When the result is **FAIR**, more frequent sampling and checking additional parameters is recommended.

When the result is **POOR**, reclamation or an oil change is recommended. The structure of the oil is damaged, in effect that the chemical bonds between the molecules have broken down, and even with filtration, the recommended dielectric values can't be achieved.

f) Resistivity (GΩm) at 20 °C or 90 °C

Property	Category	Good	Fair	Poor
Resistivity(GΩm) At 20° C	O, A	>200	20 to 200	<20
	B, C	>60	4 to 60	<4
	D	>800	250 to 800	<250
	E	>60	7 to 60	<7
Resistivity (GΩm) At 90° C	O, A	>10	3 to 10	<3
	B, C	>3	0.2 to 3	<0.2
	D	>50	10 to 50	<10
	E	>3	0.4 to 3	<0.4

This is NOT a routine test

DC resistivity of the oil is one of the key parameters to assess the transformer insulation condition; this is based on the fact that DC resistance is sensitive to oil degradation.

When the result is **FAIR**, more frequent sampling and checking additional parameters is recommended.

When the result is **POOR**, reclamation or an oil change is recommended.

g) Inhibitor content %

Property	Category	Good	Fair	Poor
Inhibitor Content %	All	Restricted to Inhibited oils, Consult oil supplier	40% to 60% Of original value	<40% of original value

This test is restricted to oils with this additive.

It would be advisable to contact the oil supplier to verify the details regarding additives.

The two most common oxidation inhibitors for transformer oils are 2,6-di-tertiary-butyl para-cresol (DBPC) and 2,6-di-tertiary butyl-phenol (DBP). The purpose of the inhibitor is to prevent oxygen from reacting with the oil. This significantly slows the aging process in the oil and the solid insulation.

If the result is **FAIR**, it is advised to top up the inhibitor level to the prescribed level per supplier instructions. It is advised to use a field professional trained in the procedure to perform this task.

If the result obtained is **POOR**, the recommendation for this scenario would suggest that the end user continues to use the oil "uninhibited," but this may lead to more rapid degradation of both the liquid and solid insulation.

It should be noted that some transformers already have a built-in oil preservation system; this is designed to keep dissolved oxygen at levels below 1000ppm. This would be in the form of a nitrogen system, a nitrogen tank or generator, or a conservator tank equipped with a rubber diaphragm (bladder). Using inhibited oils under these circumstances is not required, although it might add additional protection against oil oxidation if the preservation system ever fails. [2]

h) Passivator content

Property	Category	Good	Fair	Poor
Passivator Content (mg/kg)	O,A,B,C, D,E,F	.>70 and stable (rate of decrease < 10/mg/kg/ year)	50-70mg/kg or<70mg/kg with a significant rate of decrease of >10mg/kg/ year	<50 and decreasing at >10mg/kg/ year

Passivators, also known as metal deactivators, react with reactive metal surfaces and dissolved metals such as copper and silver and reduce their rate of reaction with compounds in the oil. This includes oxidation reactions with organic compounds and reactions with corrosive sulfur. Passivators are composed of two basic types, sulfur-based and nitrogen-based. The first suggested use of passivators in transformer oil, of which the author is aware, was in 1967 by J.J. Melchiore and I.W. Mills of the Sun Oil Company.[3]

As the oil ages, the passivator might deplete more rapidly; this depletion might accelerate when the oil is un-inhibited.

With **GOOD** results, regular sample intervals can be maintained.

With **FAIR** results, maintain regular monitoring.

When **POOR**, it is advised to remove the oil or remove the source of corrosivity from the oil via special oil treatment.

i) Sediment and sludge

This is not a routine test.

It is advised that this test is performed when the oil results indicate a high acid value and the dissipation factor is near the unacceptable limit.

The results need to be less than 0.02% by mass to be negligible. If the results return a value of more than 0.02% by mass, it is suggested that it be reclaimed; otherwise, an oil change is recommended.

Sludge in transformer tank.

j) Interfacial tension

This is not a routine test.

Property	Category	Good	Fair	Poor
Interfacial Tension (mN/m)	O, A, B, C, D Inhibited	>28	22 to 28	<22
	Uninhibited	>25	20 to 25	<20
	E	Not a routine test		
	F, G	Not Applicable		

The interfacial tension between transformer oil and water reduces during the aging process. What this means in practical terms is there is more polar compound present in the oil, decreasing the ability of an oil to serve as an insulator in the transformer system. There is a direct correlation between interfacial tension and neutralisation number. Therefore, the interfacial tension becomes a quality criterion: the oil must be changed below a predefined limit.

If results are **GOOD**, continue the regular sampling interval.

If results are **FAIR**, decrease the sampling interval.

If results are **POOR**, check the oil for sediment and/or sludge.

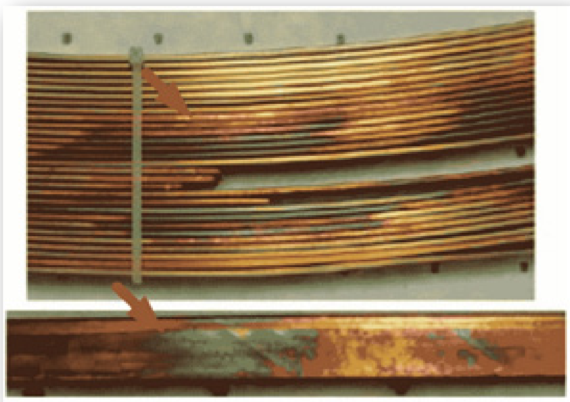
k) Corrosive sulfur

This is not a routine test.

Oil is either corrosive or non-corrosive.

The presence of corrosive sulfur in transformer oil and its effect on the transformer system can be significant. The extent of the corrosion damage caused by the sulfur can be so severe that it might cause failure of the equipment if not checked. The addition of a copper passivator can reduce the impact of this compound on the transformer system.

In a study by Doble, it has been found that rubber products used in transformers might add to the corrosivity of the oil. Nitrile rubber gaskets and hoses not approved for oil filtration might contaminate the oil with corrosive sulfur. CIGRE Brochure no 378, 2009 stipulates the necessity of corrective actions based on this institute's risk assessment study. [4]



l) Particle counting and sizing

Table 3: Particles

Table B.1 - Typical contamination levels (particles) encountered in power transformer insulating oil as measured using IEC 60970 [5].

Adaption of ISO 4406 (Edition 1999) class	ISO 4406 [6] (Edition 1987) class	Maximum count per 100ml		Contamination designation	Notes
		5 µm (equal to 6µm (c))	15 µm (equal to 14µm (c))		
Up to 10/8/5	Up to 8/5	250	32	Background contamination	Cleanliness requirement for sample bottles filled with clean solvent
11/9/6 to 13/10/7	9/6 to 10/7	1 000	130	Low	Oil Cleanliness encountered during factory acceptance test and transformer commissioning [b]
14/11/8 to 17/15/12	11/8 to 15/12	32 000	4 000	Good	Contamination level typical for transformer in service
18/16/13 to 19/17/14	16/13 to 17/14	130 000	16 000	Fair	Contamination level found on a significant number of transformers in service
20/18/15 and above	18/15 and above			Poor	Contamination level rare and usually indicative of abnormal operating conditions
NOTE: Considering the field measurements reported by various countries, it is recommended that the contamination level encountered in service should be classified as indicated in this table. A more refined classification would not be realistic in view of the variations that can occur in this type of measurement.					
[α] SOURCE: CIGRE Technical Brochure 157, June 2004 [5] [b] Statistical survey has shown that values 15/11/9 are more realistic. The cleanliness requirements may depend on the rating and shall be clarified between customer and manufacturer					

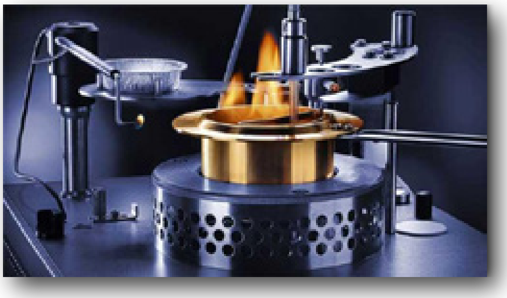
Particles: Typical contamination levels (particles) encountered in power transformer insulating oil as measured using IEC 60970 [α]

m) Flashpoint ° C

Not a routine test.

If there is a maximum decrease in flashpoints by 10%, the equipment might require further inspection. This value might differ in different countries.

It is advised to perform this test when an unusual odour is noticed, the unit has been refilled, or an internal fault has occurred.



n) PCB (Polychlorinated Biphenyls)

This test is not to determine the condition of the transformer; this is a health and safety impact test. PCB is hazardous to both humans and the environment; it is vital to test for PCBs after the retro fill of a transformer. It is also required whenever any maintenance has been done on the unit, and the possibility of contamination is present. If PCB content exceeds the recommended limits, the appropriate action needs to be taken.

Units with a PCB content of more than 50ppm require a fire safety plan, environmental protection plan, and extra precautionary measures when maintenance is done. This oil needs to be replaced, and the oil disposed of as hazardous waste, with a certificate of safe disposal issued to the equipment owner. Local regulatory bodies define the limits.

o) DGA (Dissolved Gas Analysis)

As DGA is an intricate science with a lot of data and interpretation, we will discuss this phenomenon in part II of the article. The limits for the different gases and the interpretation of this data according to international standards will be discussed in detail, forming part of the overall health rating determination of the transformer.

CONCLUSION

Transformer condition monitoring is an interlaced, highly exciting field of study. In this article, we focused on the types of tests to determine the condition of the transformer, the critical values, and the recommended actions.

The Health Index indication makes it possible to see the supposed reliability of a specific unit at a specific date and time. This makes it possible to ensure best practice application and optimised maintenance. It also make it easier to draw up a maintenance plan and action plan.

References:

- *1. IEC 60422 Edition 4.0 2013-01 International Standard (Mineral insulating oils in electrical equipment – supervision and maintenance guide).*
- *2. Oxidation inhibitor and reinhabiting oil-filled transformers, by Andy Shkolnik.*
- *3. Passivators, what they are and how they work, by Lance Lewand, Doble Engineering Company.*
- *4. CIGRE technical brochure 378, 2009 "Copper sulfide in Transformer Insulation."*
- *5. CIGRE Technical Brochure 157, 2000 "Effect of particles on transformer dielectric strength."*
- *6. Article initially published by Transformer Technology Magazine Issue 16 – December 2021 https://www.transformer-technology.com.*

About the author...

Corné Dames is a WearCheck transformer consultant. She has 20+ years' experience in the industry, having previously worked as laboratory manager for a major industrial laboratory group, focusing on transformer health. She has been intrigued by transformer chemistry right from the start of her career, particularly in the analysis of test data. Corné has vast practical and theoretical knowledge of reliability maintenance programmes.

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