A fault is not a failure

Economical and reliable transformer maintenance by holistic interpretation of insulating oil condition

ABSTRACT

The importance and cost of transformers is described and stressed in all the literature.
Transformers are one of the most important and vital links in the electricity supply chain.
Despite the very high cost related to transformer failures, the tests and diagnoses of the equipment itself, the transformer owner or a person responsible for its proper operation is faced with many diagnostic approaches and most of them are either inaccurate or unnecessary and irrelevant to individual case. Of course the lack of specialists in transformer diagnoses causes engineers in charge of transformer maintenance to rely on test and service provider companies. Naturally, the main target of those companies is to promote their business. It is very important to only carry out the tests that will not interfere with transformer operation and interpret the results holistically in the transformer exploitation context, manufacture, internal organisation politics and many other parameters. Missing one or several parts of the testing can lead to completely wrong overall diagnosis.

Keywords:

Transformer oil analysis, Dissolved gas analysis, Risk management, Corrosive sulfur.

Introduction

A few misconceptions about the transformer industry:

- „If my old transformers are still in good condition, it is not necessary to worry about replacing them.“
- „Transformer technology is the same as it was 50 years ago; same steel, same oil and same cellulose.“
- „We intend to keep an old transformer in operation without maintenance until it fails, than replace it with a new one.“
- „The testing guidelines published in some of the standard guides also apply to my transformers.“

All those misconception can lead to very costly outcomes, e.g. replacement of a good quality old transformer by a less robust new transformer, or a dramatic failure scenario.

Transformer maintenance is commonly compared to medicine, and as such, it has to be based on reliable tests and diagnoses which must be carried out by a specialist who is familiar with the latest technologies and issues regarding transformers and who is able to recognise specific conditions of the specific piece of equipment. Like human beings, transformers differ one from the other, even the ones made by the same manufacturer and in the same housing, and the twins.

All those parameters impose a real dilemma for the transformer owners and contribute to discrepancies in proper maintenance, reliable electricity supply and shareholders' profits.

The transformer technology and demands change dramatically these days and the transformers are no more „low tech".

Today a much more compact transformer has to transform more energy at higher voltages and in significantly less space. These requirements impose a continuous search for new materials, new designs and new maintenance strategies to enable longer transformer operation.

This paper will focus on insulating materials inside the transformers. Those materials are responsible for the majority of failures and catastrophic events but, nevertheless, can be monitored during transformer operation:

1. Choosing the right oil type for each transformer type. The variety of insulating oils increase and change constantly. 50 years ago, users had access to a very limited assortment of oil types, such as the well known PCB. Inhibited mineral oil with non-strict demands, such as low oxidation stability and lower breakdown voltage, was also available. At this time, the oil test limits were not mandatory, e.g. the former IEC60422 allowed 0.5, acidity. Back then, almost all oil types were suitable for any transformer.

2. With such variety of insulating oils today, it is very difficult to establish the differences and advantages of so many oil types and liquids. Of course, the oxidation stability coupled with potential of sulfur corrosion and additives are the main concerns for all industries due to too many recurring incidents related to these problems. The transformer purchaser chooses the liquids manly according to the initial price which can lead to very costly outcomes. However, the price is not a good criterion as some of the most expensive insulating liquids can also damage transformers. The only solution is to have the correct unbiased knowledge.

3. Solid insulating materials are also challenging to implement. Although there are very durable insulation materials, this is not always the best choice pricewise. The designer and the transformer owner have to know and understand the needs and problems of all materials and their compatibility.

Transformer maintenance is more of a subjective art then an accurate science.

Since 1885, transformers are responsible for transportation of the electrical energy from the power station to the end user. Since then, the principle of transformer operation did not change significantly. However, many researchers still continue the efforts to make them more efficient, economical, and environmentally friendly. These features are often results of conflicting requirements for high reliability and improving operation conditions. In the new competitive environment of post-privatisation age, transformers should transmit more MVA with less insulation for longer periods of time.

Compared to dry transformers, oil filled transformers have the advantage of greater possibility of oil tests.

V.V. Sokolov et al. [1] stated that more than 70% of transformer condition insight can be gathered from oil analysis. Most transformer owners worldwide rely mainly on oil tests to diagnose abnormal conditions in transformer operation. Oil tests may even be the only planning method for transformer operation to some utilities and users.

Major roles of oil inside the transformers are:
- Oil is a part of insulating system along with cellulose.
- Oil must have acceptable dielectric properties.
- Oil has to flow through the internal parts of the transformer.

Like human beings, transformers differ one from the other, even the ones made by the same manufacturer and in the same housing, and the twins.

- Insulating oil has to efficiently transfer transformer heat.
- Oil has to safely store important data about transformer health.
- Transformer oil should remain in an acceptable condition for the most of transformer life, at least 25 years.
- Transformer oil should not harm the environment.
- Insulating oil should not ignite easily.
- Transformer oil has to dissolve impurities and sludge at maximum length.
- Mineral insulating oil should not have lubricant properties.

Routine oil tests are used to obtain maximum information with minimum investment. In addition, there are supplementary tests and special tests that can indicate a specific condition of the oil or the transformer.

Oil testing process is divided into three separate parts:
- sampling
- analysing
- diagnostics or conclusions based on the results and condition of the transformer

All those steps should be performed according to only one standardisation body, e.g.: IEC, ASTM or other regional or national standards. IEC transformer oil sampling and test standards are precise and the user who abides by these standards can be assured that they will end up with reliable diagnosis. Other standardisation bodies also provide valuable sampling and testing procedures. The users should always make sure they follow all the recommendation and instructions for sampling via testing and up to the final diagnosis. Although most of the steps are clearly indicated, the quality of the diagnosis depends on the experience of the laboratory staff and the person who determines the final diagnosis.

In most cases, the electrical and physical tests are performed only after receiving a warning sign from the oils tests.

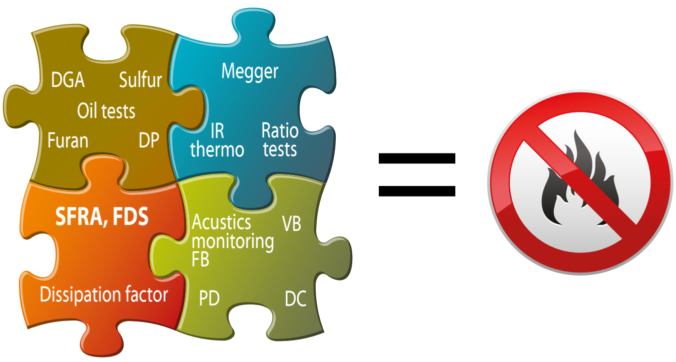


Figure 1: Correct interlacement of all the tests can avoid unpleasant situations

Transformer oil specification and limit values were changed dramatically during the last few years. Those changes reflect the need for an improved final product that will fulfil demands from transformers. In the past, the insulating oil contained more natural antioxidants that prolonged their life but affected the electrical properties. The new generations of transformer oil meet more stringent electrical property requirements and are refined accordingly. Now more users swap non-inhibited products to oils that include antioxidant inhibitors. Those oils have better electrical properties and provide better oxidation stability. However, they depend more on the antioxidant content. The abundance of aromatic molecules and non-carbon atoms in modern oil is reduced to improve the electrical properties.

2. Transformer oil tests are categorised in two major groups:

Oil tests for evaluation of transformer condition: Dissolved gas analysis, Furan compounds in oil, dissolved metals, and oil tests for evaluating oil conditions:

2.1 Dissolved gas analysis (DGA) is the single most popular and most indicative test for evaluation of condition of the transformer in service [2].

Along with the evident advantages, a DGA technique has a few important drawbacks. Here is a brief description:

The main goals of DGA-based diagnosis methods are:
- to suggest the severity of the failure and to plan maintenance
- to establish a prognosis, which consists of inferring the apparatus diagnosis and possible evaluation of the malfunctions later on. Since these methods are prognostic, the results will have subjective aspects.

Transformer data with significant impact on DGA evaluation are:
- tap changer type
- manufacture and construction technology
- oil type
- oil preservation system type
- loading condition
- maintenance

Dissolved gases can be present in transformer oil due to following reasons:
- natural aging of the materials
- oil oxidation
- gases generated due to transformer overload
- gases generated due to a fault
- other specific causes

Major DGA advantages compared to other diagnostic methods are:
- can be used to check almost all transformer internal components. Like the blood in living beings, the oil reaches all internal transformer parts.
- sensitive method; capability to detect incipient transformer malfunctions using highly sensitive detectors.
- data gathering; the test reveals problems than occurred during the sampling intervals.
- economical sample intervals; due to gas production mechanism, it is possible to test the health of the unit once per year.

Major DGA disadvantages are:
- The technique is sometimes too sensitive.
- According to Transformer Cigre WG [3], 30% of data regarding transformer health cannot be revealed by the DGA.
- Some rapidly occurring failures damage the equipment before they can be detected by the DGA, even with the newest online monitors.

DGA has to be performed by skilled personnel from the samp-

ling phase up to the diagnosis. All test stages are susceptible to error. Some important aspects:
- sampling: Glass Syringe is preferable oil container. The oil has to be representative, i.e. enough oil has to be allowed to flow before the sample is taken because in cases of active failure, the sampling can assist in locating the source of gases.
- analysing: There are many methods of testing dissolved gases in the oil. Each method can measure gas in the oil differently as each method involves different extraction or uses different measurements. The basic assumption that gases in oil obeyed to Ostwald coefficients in all measure techniques was proved to be incorrect by a different researcher [4], [5]. Apart from the methods described in the standards, some portable and online device use non-standardised techniques. Detailed review of some of those techniques can be found on the CIGRE report [6]. Figure 2. shows a comparison of repeatability of a portable device vs. the standard head space method.

The only way to overcome these difficulties is to use gas in oil mixtures with known concentrations. Although the existing standards describe methods for preparation of such mixtures, most of the users avoid preparing them due to the procedure complexity. Commercial gases in oil mixture are very limited and expensive, and do not provide reliable drawing calibration curves.

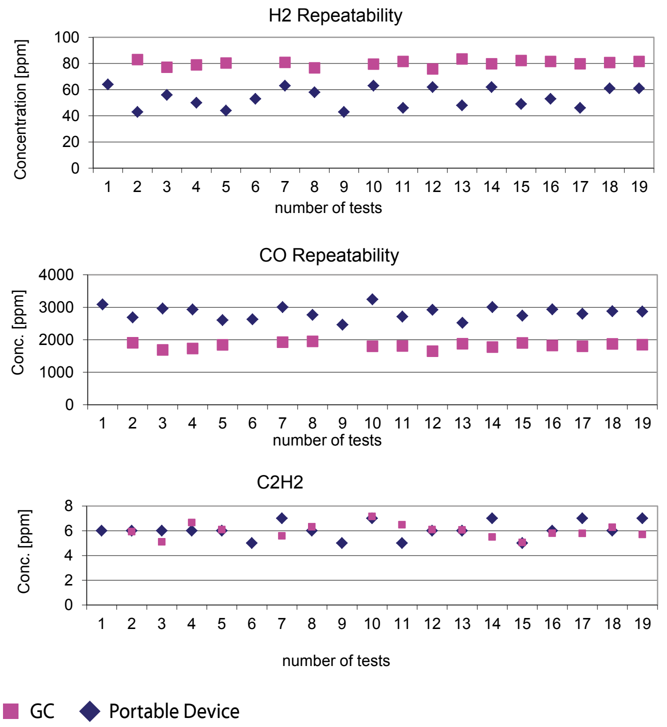
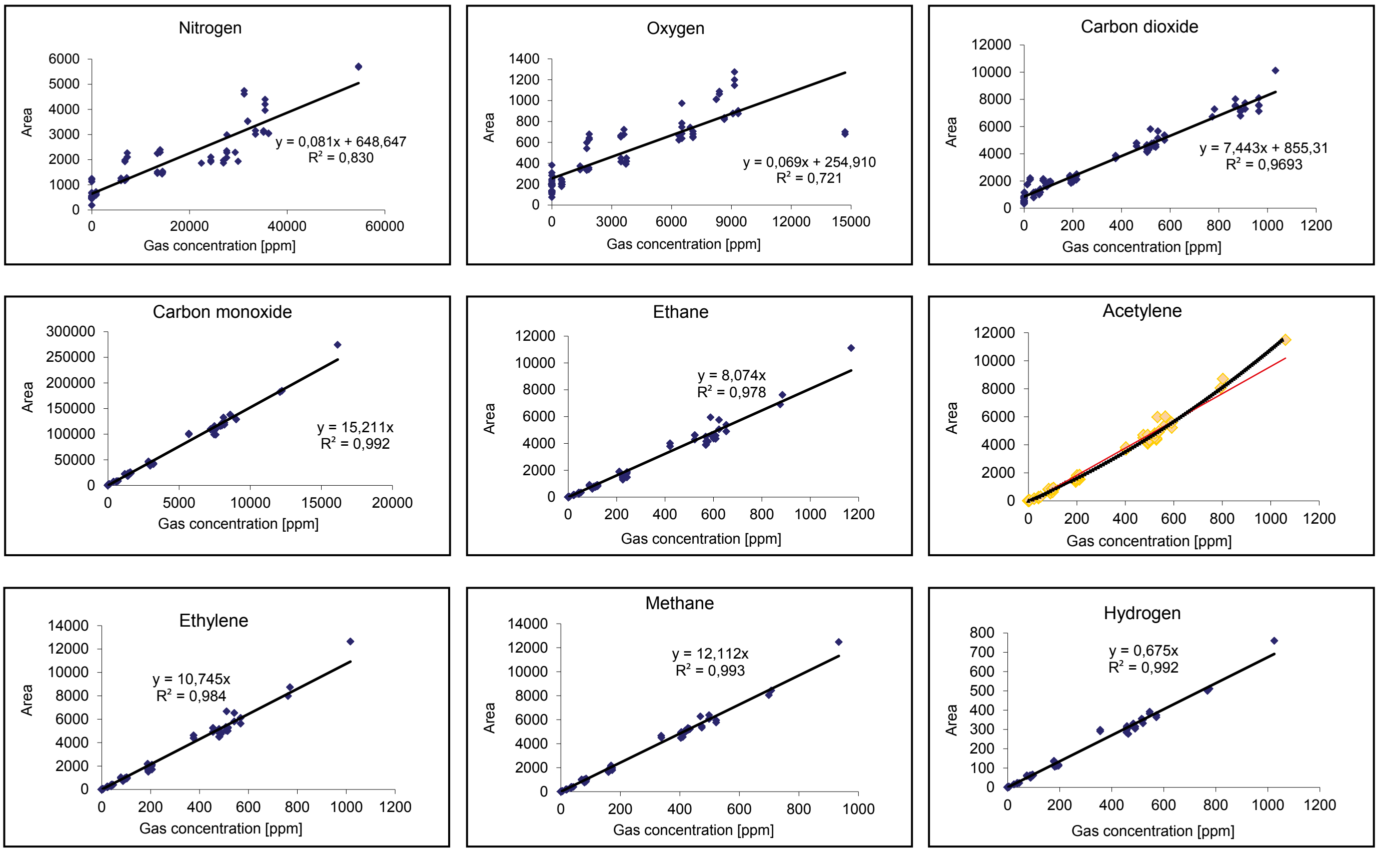


Figure 2: Comparison of repeatability of 2 DGA measurements, Head space according to IEC60567, 7.5 and portable device.



Nitrogen	Oxygen	CO_2	CO	Ethane	Acetylene	Ethylene	Methane	Hydrogen	
150	50	0,5	0,5	0,5	0,5	0,5	0,5	1	Detection limit
4585	14276	139,5	109,5	109,5	104	106	111,5	109,5	Commercial gases
30211	9040	178	113	129	118	111	111	107	Concentration measured by IE

Figure 3: Calibration curves at Israel Electric and comparison to gas in oil commercial mixtures

Table 1: Comparison of DGA test methods and current IEC and ASTM

DGA method	Calculation	IEC 60567	ASTM D3612	Compatibility & Remarks
Vacuum extraction by partial degassing	Ostwald coefficient gas in oil and gas peaks calibrated by gas in gas	7.3	A	Yes Suitable for factory test
Stripping extraction method	Efficiency coefficients and gas peaks calibrated by gas in gas	7.4	B	Yes Not suitable for factory test
Multi-cycle vacuum extraction using Toepler pump apparatus	Absolute volume of gases and gas in gas calibration	7.2	No	Best and absolute method
Headspace method	IEC calibrated by gas in oil standards ASTM by Ostwald coefficients and gas peaks calibrated by gas in gas	7.5	C	No The repeatability and accuracy of method is variant due to difference in injection and calculation methods. Not suitable for factory test

The laboratory or transformer expert should issue a qualitative diagnose based on reliable results from representative oil from a specific transformer. Here are some options:

- to use any of the existing mathematic models or software to prepare the transformer diagnosis.
- to use internal prepared models for diagnosis.
- to take advantage of personal experience based on as many successful failure diagnoses as possible.

According to this concept, we can reveal most transformer faults and avoid devastating failures. Here are some examples:

Table 2: Diagnosis methods and related problems

Method	Principle
Key gas	Gas identification and proportion
Rogers	Ratios of 3 combustible gases
Donnenberg	Ratios of 4 combustible gases
IEC 599	Other ratios of same 4 gases
Duval Triangle	Graphic Monograph – Triangle
IEEE C57-106	Absolute concentration and increase rate
Japan method	Graphic Monograph – Rectangular
PowerGen Method	Score for each gas, ratio and other oil tests
Artificial intelligence	Different calculations approach still research
CIGRE TF11	Calculations of 90% values for transformer „families" – with similar design and operati on conditions.

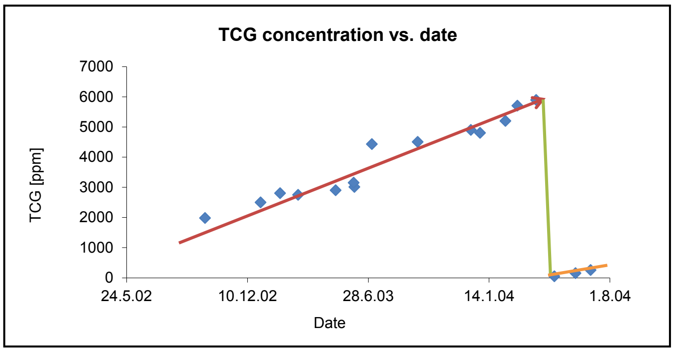


Figure 4. Case 1 Transmission transformer, DGA + findings

Figure 4. shows a minor failure that was discovered by an accurate DGA test so serious consequences were avoided. This case emphasises the importance of taking accurate measurements.

Most transformer owners worldwide rely mainly on oil tests to diagnose abnormal conditions in transformer operation

Date	TG	H2	CH4	C2H2	C2H4	C2H6	CO	CO2
16.12.2001	6	26	49	0	34	24	423	1482
12.6.2003	5	44	66	0	39	29	825	4125
11.2.2004	7	43	77	0	44	36	796	3973
26.3.2004	8	375	110	139	70	34	863	4438
30.3.2004	6	350	104	123	67	32	797	4294
13.4.2004	6	346	103	129	67	32	788	4160
10.5.2004	7	332	113	115	71	32	907	4254
5.8.2004	8	259	114	31	69	30	876	4869
18.10.2004	7	199	117	12	67	31	880	5120
17.5.2005	9	112	121	1	71	42	882	5115
15.5.2005	4	60	60	1	37	22	429	2781
29.8.2005	8	728	155	187	91	43	884	8400

Figure 5: Case 2 double winding failure. The failure was revealed twice.

Figure 5. shows an interesting case which confirms that any sign of acetylene indicates a failure. If the transformer still operates after Buchholz relay there is a chance it could suffer a devastating failure.

2.2 Oil quality tests described by main standardisation bodies

Table 3. displays some major differences between IEC [7] and ASTM [8].
The user has to know the exact method in order to test the oil. Each method can generate different values accordingly.

2.3 Proficiency tests for insulating oil tests

Proficiency tests or Round Robin comparison is the single most important tool for laboratory performance evaluation.
The transformer owner has to be totally confident in the result issued by the contracted laboratory. One of the conventional practices in the industry is the cross section test, i.e. sending the same oil to several laboratories and comparing the results.

The quality manager of each laboratory should make effort to estimate the results of each oil test in the laboratory if they are also performed by any other quality accredited laboratory.

Proficiency tests are carried out by 19 worldwide laboratories, some of them well known and accredited and others without accreditation and poor quality control. Figures 10. and 11. show laboratories that take the test quality into account and achieve results much closer to the average.

It is not surprising that only dissipation factor shows similarly scattered results within both laboratories groups. Three other analyses are more sensitive to the quality of the procedures and the operator skills.

Table 3: Comparison of major test methods for insulating oil of the 2 major standardisation bodies.

Parameter	Test type	IEC	ASTM	Compatibility
Break down voltage	Routine	IEC 30156	D1816 in service D877 new oil	No, different condition test
Water in oil	Routine	IEC 60184	D1533	Yes, partially dependent on top oil temperature?
Acidity	Routine	IEC62021-1 Potentiometric IEC62021-2 Colorimetric	D664 Potentiometric D974 Colorimetric	Partially, different condition tests but results on the same scale if the tests are properly carried out No, absolute method for acidity
Dissipation factor	Routine	IEC60247	D924	No, different condition test
Antioxidant content	Routine	IEC60666	D2668	Partially, IEC more sensitive and accurate
Interfacial tension	Complementary IEC Routine	D971, to be changed	D971	Yes, accurate with automatic equipment

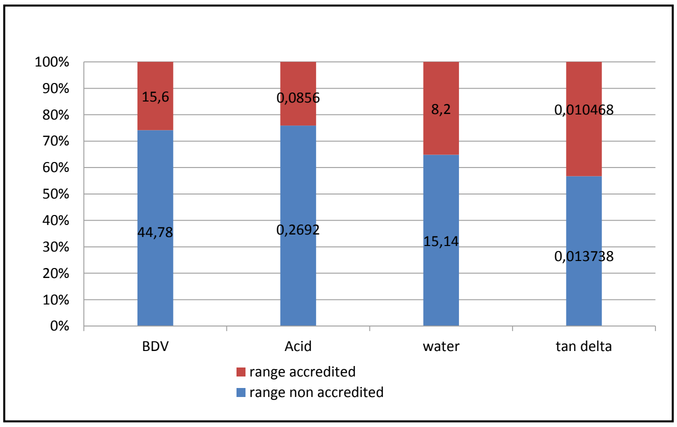


Figure 6: Graph showing scattered results from the accredited laboratories and the non-accredited ones with poor quality test programme.

Scattered values can end in erroneous diagnosis regardless of how sophisticated the software that makes those recommendations is.

Some laboratory results can cause incorrect costly maintenance or leave the transformer untreated.

The figures represent the limits according to IEC 60422 standard: fair and poor values.

We can make the following conclusions from this study:
- For measurements without obtainable standard materials, the only "true value" is the average obtained from as many qualitative laboratories as possible.
- Proficiency test is the only available option to control transformer oil measurements.
- Accredited laboratories achieve less scattered results than the non-accredited ones.
- Scattered results can also occur in accredited laboratories.
- Round Robin points to inaccuracies and restores the quality of oil measurements.

2.4 Furan compounds, product of cellulose decomposition in oil

Measurements: according to IEC 61198 and qualitative laboratory performance with controlled output. The laboratory has to perform comparison (proficiency test or PT) with other laboratories at least once a year.

Frequency:
- transformer up to 30 years of age, once every 2 years
- transformer over 30 years of age, once a year
- new transformer should be tested a month after energising
- a month after each oil treatment

Although furan compounds measurement has been performed for more than 15 years, no reliable diagnosis has been developed by any standardisation body regarding the DGA and oil analysis. In furan diagnosis, the experience and knowledge of the expert who performs the diagnosis is much more important.

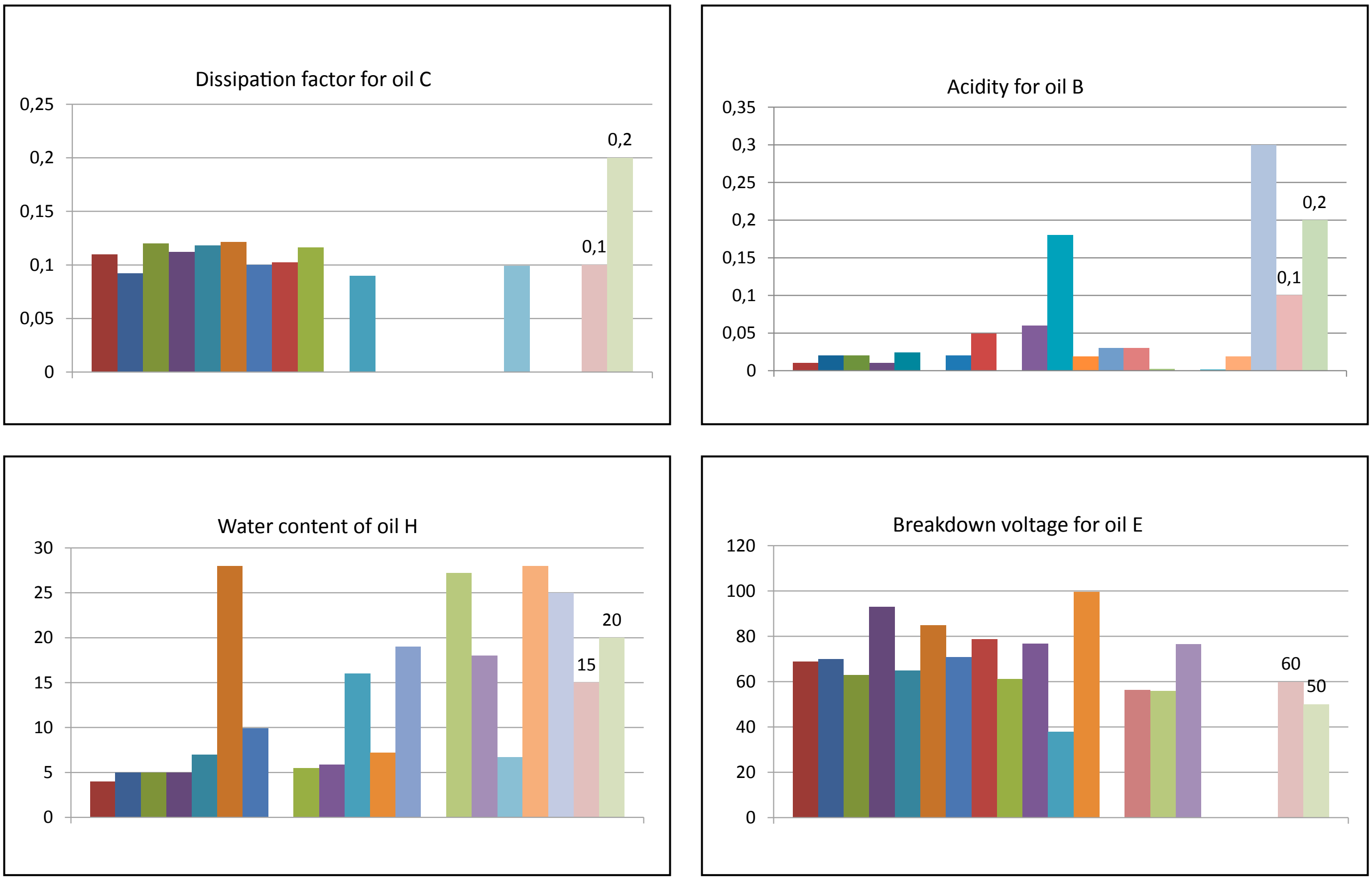


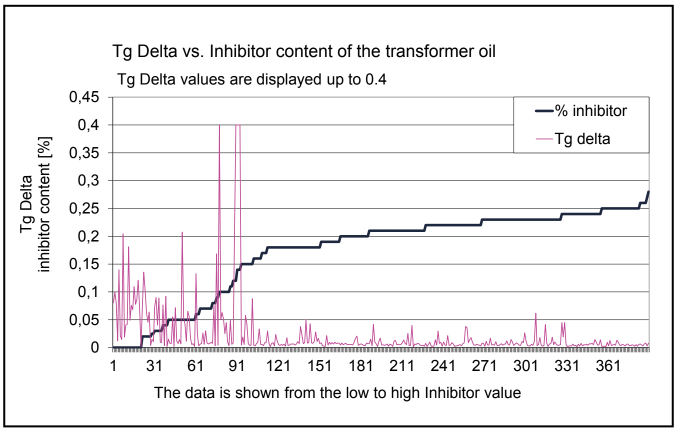
Figure 7: Comparison of some oil tests within 19 laboratories.

3. Correlation between oil parameters

Based on reliable oil tests at Israel Electric laboratories, we correlate different parameters such as the acidity and dissipation factor with the concentration of the anti oxidant inhibitor for 400 transformers. Not surprisingly, we found that if the inhibitor content is above 40% of the initial level, then both parameters will be in good condition without an exception. If the inhibitor has been consumed, then the acidity and dissipation factor can be abnormal.

No correlation between water content and inhibitor content was found.

We found that furan compounds appear only in cases of high moisture and high acidity.



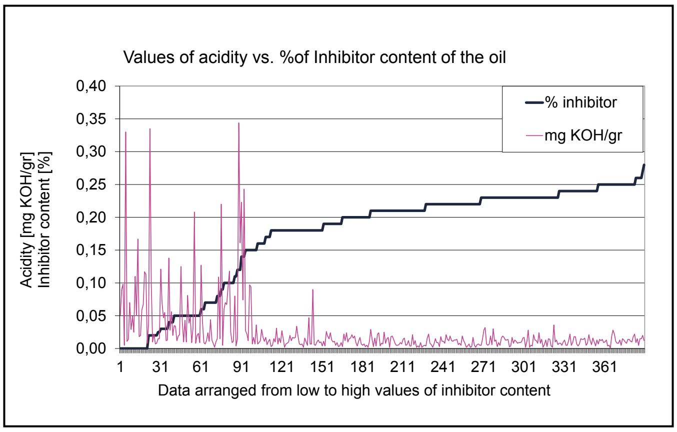


Figure 8: Inhibitor Survey in Israel Electric

Correlation between oil quality and DGA and Furan:

- Humidity, elevated temperature, electrical and mechanical disturbance, and impurities in oil affect the transformer isolation (oil and paper). Gases and furans are generated according to the fault severity.
- During the rapid oil ageing, the inhibitor disappears and consequently the acid rises. The process continues with the production of sludge, the sludge being deposited on the hot area inside the transformer and the whole process is intensified by the positive feedback. The sludge prevents heat dissipation through the oil.
- The acid and sludge are one of the factors that affect the dielectric integrity of the oil/paper isolation. Destruction of the cellulose produces water that amplifies the aging process.
- The transformer life can be improved by:
  - preventing impurities inside the transformer
  - keeping humidity and oxygen away by proper sealing
  - maintaining the inhibitor level
  - efficient cooling

4. Potential sulfur corrosion

Sulfur corrosion is one of the most researched subjects in the transformer industry since the beginning of the millennium. Several major organisations such as Cigre [9], Doble [10], Sea Marconi [11], Terna [11], and others have already published extensive reports on this topic.

According to the reports, the DBDS substance causes sulfur corrosion. The oils at Israel Electric were tested for DBDS in 2005 and no evidence of this substance was found.

In 2009, we discovered that some of our important GSU transformers suffer the consequences of sulfur corrosion despite no presence of DBDS in the oil. Figures 9. to 11. show several internal copper parts covered by the product of sulfur corrosion phenomena.

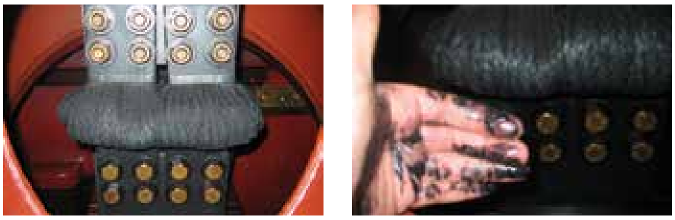


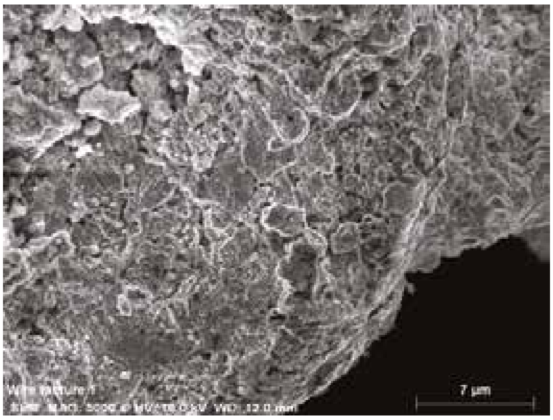
Figure 9: LV side (10.5 KV) flexible connection from a GSU transformer affected by sulfur corrosion

Figure 10: Typical contaminated bolt from a GSU transformer affected by sulfur corrosion

We discovered the phenomena before the failure occurred due to intensive electrical and chemical testing.

The affected parts were examined by Electronic microscope. Figures 9. and 10. show some of the findings on the affected wires.

We conclude that the mechanism of sulfur corrosion in our oil type is different from the mechanism suggested by CIGRE WG A2-32 [11]. The explanation of the sulfur corrosion mechanism in oil without DBDS is still in progress. Also the mitigation of this phenomena and monitoring of the severity will be discussed in the new CIGRE WG A2-40, to be published in its 2014 report.



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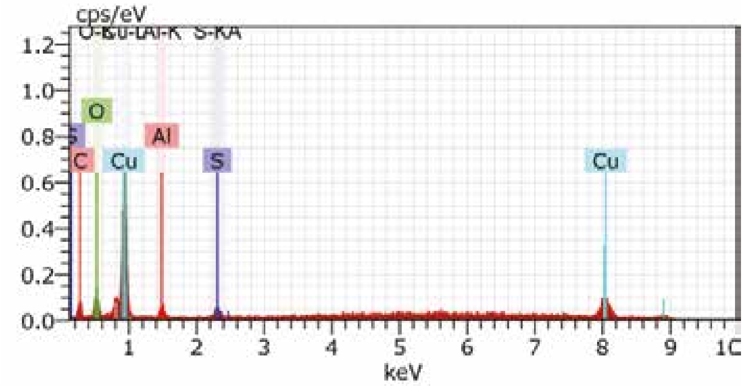

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Figure 11: Metallurgic test. Copper wire on SEM

Conclusion: How to improve it?

Our formula for optimal chemical service in the electrical industry:
- comparison to standard materials and other laboratories abroad
- International Standard Societies membership and community support from fellow labs
- maintaining quality database for each transformer
- good communication with transformer owners and clients
- dedicated and reliable service

The best DGA method for special tests such as heat run test, is a multi-cycle vacuum extraction using Toepler pump apparatus but IEC head space, 7.5., is the most sophisticated and time consuming for DGA routine.

Out of the routine oil tests, the most important one is the antioxidant content test if the oil contains it, followed by the moisture, BDV, dissipation, IFT, and acidity test.

For sulfur corrosion CCD (covered conductor deposition) test by IEC or DOBLE must be in line with DIN and ASTM. The disadvantage of those methods is that they are qualitative only. SEA Marconi published a quantitative method recently that is at the end of the standardisation process.

The main and most important issue is to understand the exact need of each transformer based on the condition, remaining service life and even the organisation politics.

Conducting tests with single quality laboratory can greatly assist in reliable diagnosis and help in making the right decision for high investments.

Knowledge exchange of users and experts worldwide is also very important as well as to be up to date with the latest developments and issues that arise constantly in this industry.

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