EXPERIENCES WITH APPLICATION, DIAGNOSTIC VALUE AND IMPACT ON ASSET MANAGEMENT OF INSULATION OIL ANALYSIS

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Abstract: This paper presents and discusses the Swiss experiences with the application, analysis, value and impact on asset management of regular insulation oil diagnostics, which includes dielectric-chemical parameters, dissolved gas analysis and furan analysis. Most frequently oil laboratories determine the dielectric-chemical parameters according to IEC 60422. Here the interfacial tension, neutralization number (acidity), colour number and dielectric dissipation factor tangent delta (conductivity) allow for collecting a consistent record – even over decades – on the ageing performance of the observed oil-paper-insulation. This is not true for moisture content and breakdown voltage. Though these parameters are closely linked to each other (moisture strongly influences breakdown voltage), the authors could not establish a dependable relationship between these two parameters and the other ageing indicators. As for the limits given by standards, the authors observed that for most insulation oils the parameter interfacial tension (with 20 mN/m according to IEC60422) is the first which does not meet the requirements of the standards. Other parameters follow only after decades of operation. Therefore we conclude that the present limit is too high and propose to lower it. For the DGA (dissolved gas analysis) the paper presents the 90 % values of oil-filled HV equipment in Switzerland, grouped by power transformers and instrument transformers. These values are mostly lower than given in IEC60599. The most frequent DGA failure type is local hot spots, indicated by excessive production of ethylene. This is followed by partial discharge activity.

1 INTRODUCTION

Insulation oil analysis is a simple and at the same time very effective method to evaluate the condition of liquid-filled HV equipment. For example, about 1 million oil samples are analysed worldwide only for dissolved gas analysis (DGA), [1]. The number of dielectric-chemical tests (including breakdown voltage, water content, neutralization number etc.) can be estimated to be even larger.

Though measurement procedures and standards are in place since many decades, the authors of this article would like to present their positive and negative experiences. These experiences on insulation oil analysis were collected over decades and comprise the analysis of several 10’000 oil samples. The authors also would like to evaluate the value of individual parameters measured during oil analyses, which includes measurement principle and diagnostic usefulness, as well as limits given by standards.

2 CALCULATION OF 90 % VALUES FOR DGA ANALYSIS

For gases dissolved in insulation oil, no absolute concentration limits are given by standards but the use of 90 % values is proposed. For example, IEC 60599 recommends users to calculate gas ratios and proposes fault diagnoses only when gas concentrations in service are above 90 % of typical values. Reasons for this recommendation are that for lower concentrations faults are less likely to occur and measurement accuracy is higher for higher concentrations, [2].

This standard also recommends each utility to calculate its own typical values, since these are dependent on the specific equipment and operating conditions.

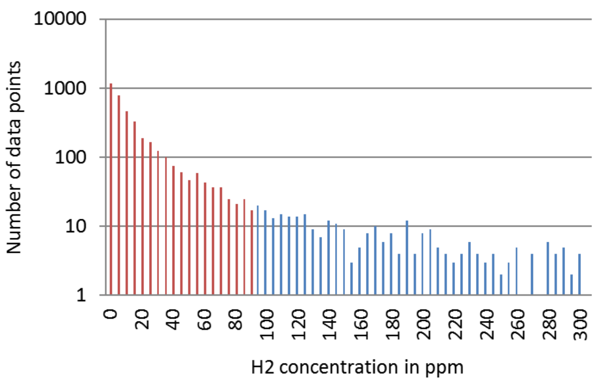


Figure 1: Histogram data for the concentration of hydrogen. The 90 % data are red, while the data exceeding 90 % are blue.

The DGA database of the FKH consists of measurements on transformers from Swiss grid operators, mainly of the German-speaking part of Switzerland, collected between 2004 and 2015. The transformers service times range from virgin transformers to 60 years old transformers. For calculating the 90 % values the database was at first cleaned from inconsistent measurements or transformers with communicating OLTC. Then three groups were formed: (1) transformers, (2) instrument transformers, (3) bushings and cable terminations. The data were grouped in a histogram and the 90 % values calculated for each gas and each equipment group. Figure 1 exemplarily shows the histogram for hydrogen, where the data below 90 % are coloured in red, while the data exceeding 90 % are blue.

Figure 2 compares the typical gas concentrations in Swiss power transformers (blue) with the 90 % ranges as given for transformers without commuting OLTC in IEC 60599 Ed. 3 [3]. This new version of the standard will be published End of 2015. For most gases the Swiss values lie in the lower area of the worldwide collected IEC values. This is particularly apparent for methane CH_4 and ethane C_2H_6, gases indicating thermal stress. One could derive that the thermal stress in Swiss transformers is below the worldwide average. The somewhat higher concentration of acetylene C_2H_2, pointing on high energy discharges, comes from a number of transformers with communicating OLTC which were not removed before data analysis. For the somewhat higher value of carbon monoxide CO (680 ppm FKH value vs. 600 ppm Cigré survey) the authors would like to point on the earlier edition of IEC 60599 (1999), where carbon monoxide ranged from 540 to 900 ppm; therefore in-line with the here found values.

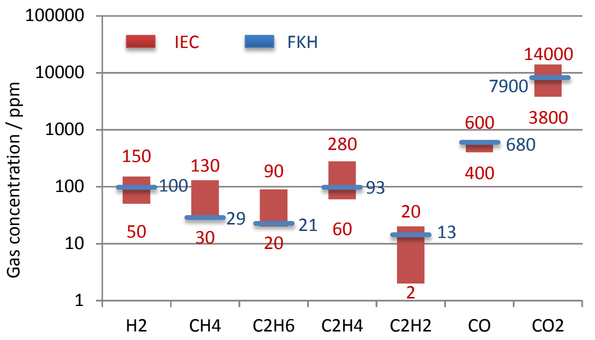


Figure 2: 90 % typical gas concentration values observed in Swiss power transformers (blue) in comparison with the 90 % ranges as given in IEC 60599 Ed. 3 [3].

Figure 3 compares the typical gas concentrations in instrument transformers in Switzerland (blue) with the 90 % concentrations from the new version of IEC 60599, which will be published end of 2015. For most gases the concentration is lower than in the worldwide fleet. This is particularly eminent for ethylene C_2H_4 and acetylene C_2H_2, gases pointing on hot spots and high-energy discharges. These gases occur very rarely in the FKH database. The somewhat higher values of ethane C_2H_6 originate from a number of instrument transformers from a Swiss manufacturer showing this peculiarity. Though the gassing tendency is somewhat irregular, no failure was found related to this gas signature.

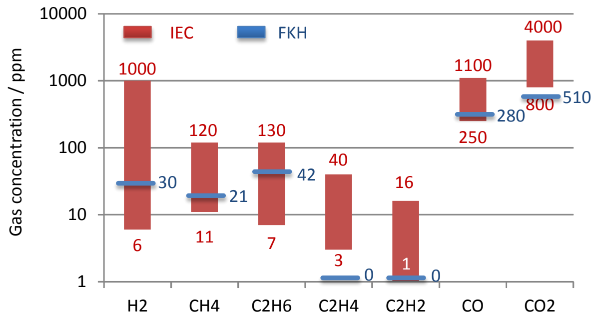


Figure 3: 90 % typical gas concentration values observed in Swiss instrument transformers (blue) in comparison with the 90 % ranges as given in IEC 60599 Ed. 3 [3].

The 90 % values as given in Figure 2 and Figure 3 are one criterion for discrimination between healthy and possibly faulty equipment. Additional conditions are:

- trends in comparison to the last analysis,
- the age and operating mode of the equipment,
- historical maintenance actions,
- design-specific and
- manufacturer-specific criteria.

3 MOST FREQUENT FAULTS IN POWER TRANSFORMERS

This section discusses the most frequent faults found in power transformers in Switzerland as well as typical maintenance actions. Faults are identified by a transgression of limits of relevant standards (e.g. IEC 60422:2013) or a suspected fault based on a diagnostic measurement.

3.1 General Ageing of Oil and Paper

The most frequent reason for an indication is general ageing of oil and paper. This is found by the analysis of dielectric-chemical parameters after IEC 60422, [4]. Of all analysis made by the FKH oil laboratory, 16.1 % do not meet the limits of IEC 60422. The dielectric-chemical indication is often accompanied with high concentrations of carbon mon- and dioxide (CO, CO_2, pointing on oxidation) and furans (pointing on paper degradation, also by hot spots).

Maintenance actions after this diagnosis are oil treatment with fuller's earth or, in particular for small transformers, the replacement of the transformer. Oil exchanges are usually not carried out, unless the original was of poor quality.

Figure 4 exemplarily shows the development of various dielectric-chemical oil parameters of a 132 kV, 21.8 MVA generator step-up transformer, which was built in 1995. After treatment with fuller's earth the improvement of the oil condition becomes graphically visible. After the authors experiences, the life time of transformers can be prolonged by 15-20 years with such treatment.

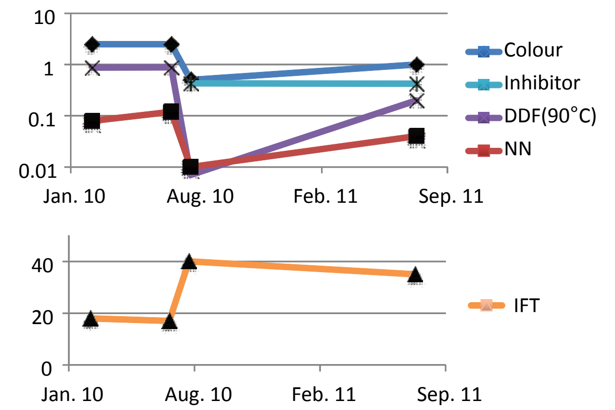


Figure 4: Oil condition before and after oil treatment with fuller's earth

Before the oil is processed with fuller's earth, in many cases the prospective effectiveness of this maintenance action is verified by a laboratory experiment. For this an oil sample is treated with fuller's earth and thereafter aged in an accelerated ageing test after IEC 60125, method A. The oil sample in Figure 5 obviously passed this test.

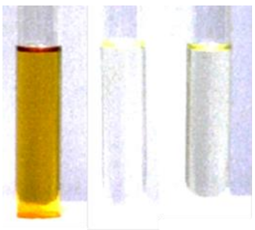


Figure 5: Oil appearance and colour before and after treatment with fuller's earth and after an accelerated ageing test (l.t.r.)

3.2 Thermal Fault – Hot Spot

Statistically the second reason for possible problems are thermal faults or hot spots. This fault is identified by dissolved gas analysis and the dominating gas ethylene, which is usually generated at temperatures of 300-700°C. Statistically 8.9 % of all DGA samples show the signature of this fault.

After our experiences the most frequent reasons for a thermal fault are defective contacts between bolted connections, gliding contacts, contacts in the selector switch of the OLTC and other connection problems.

Figure 6 illustrates a thermal fault, found in a large single-phase generator step-up transformer (181 MVA, 16/220 kV, 1984). The concentration of ethylene (C_2H_4) rose to 170 ppm, while 93 ppm is the 90 % value. Even more peculiar is the CO2-concentration with 103000 ppm, pointing on a problem in paper. Also the furan concentration supported the assumption of having paper involved.

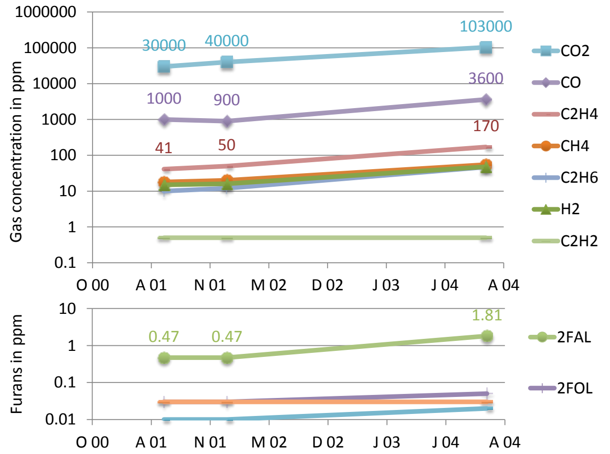


Figure 6: Gas and furan concentration in a generator step-up transformer with the signature of a thermal fault

The transformer was then inspected and burnt insulation paper found at the connection of the LV winding to the LV bushing, Figure 7. Obviously this paper-wrapped copper was not sufficiently cooled or simply under-sized.

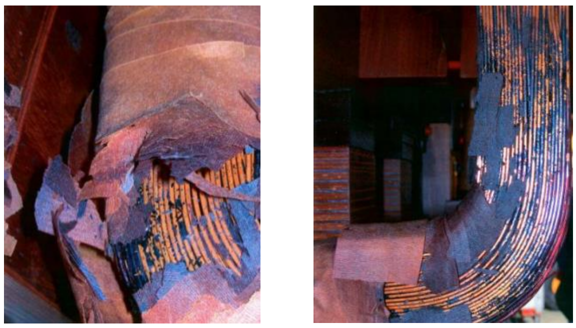


Figure 7: Connection of LV winding to LV bushing at a 181 MVA generator step-up transformer with obvious signs of pyrolysis

Follow-up actions after the indication of a thermal fault are:

- Repeated oil sampling and gas analysis
- Frequent switching of the OLTC or selector switch to remove possible coatings
- Localisation with electrical measurements like dynamic winding resistance, impedance, frequency-dependent impedance (FRSL) and sometimes FRA. However, often these electrical measurements do not give a dependable diagnosis.

3.3 Partial Discharges

Statistically the third reason for an indication are partial discharges. This is identified by dissolved gas analysis and the concentration of hydrogen and its relationship to methane and acetylene. Statistically 6.1 % of all DGA samples point on partial discharges.

Figure 9 illustrates the sudden nature of a PD fault: this transformer (220/150 kV, 140 MVA) was manufactured in 1960 and had so far no abnormalities. Then a simple gas monitor gave alarm and was confirmed by laboratory DGA. Fortunately the gas levels did not increase. Due to the operators experiences with other transformers of this type the connection to the HV bushing was known to be the reason. The risk was evaluated to be low and the transformer was left in service.

Figure 8: 220/150 kV and 140 MVA single phase transformer

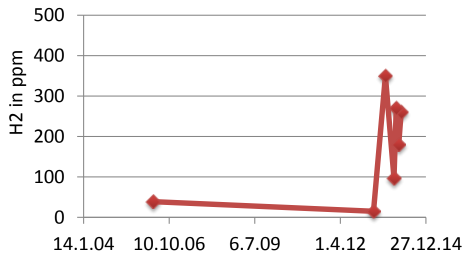


Figure 9: Sudden increase of hydrogen in oil due to partial discharges at a bushing connection

These sudden faults can be much more harmful. A generator step-up transformer (400/220/10 kV, 200 MVA, 1993) was sampled every 4-5 years. Then the Buchholz relay tripped, having 680000 ppm hydrogen and 19000 ppm acetylene, a sign of high-energy discharges. The failure was that severe, that even an electrical PD test could not be carried out because of an internal short-circuit. Figure 10 shows the gas concentration over a period of 10 years including the oil sample which was taken after the trip of the Buchholz relay.

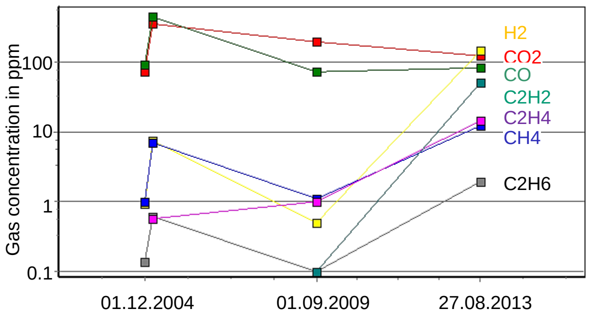
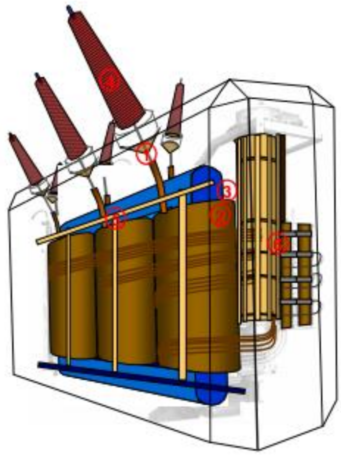


Figure 10: Gas-in-oil development of a transformer which failed due to an internal arc

After identification of a PD fault usually an electrical PD measurement is carried out with the aim to localize the defect (electrical and acoustic measurement). Figure 11 shows the typical locations of power transformers based on experiences gathered by measurements on 259 units [5].



(1) Output duct cone or bellow
(2) Humidity in oil and cellulose
(3) Free particles
(4) Bushings
(5) Clamping structures and fixation of connections (impregnation)
(6) Contact problem in tap changer

Figure 11: Typical locations of PD in power transformers

Depending on the risk, the active part will be repaired or the transformer is left in service. In such case usually on-line monitoring is applied.

3.4 Experiences with On-Line Monitoring of Transformers

On-line monitoring is applied to minimize the risk related to faulty transformers and for condition monitoring of very important transformers in power plants and substations.

Dissolved gas analysis with gas-selective on-line monitors is the most frequently applied type of transformer monitoring in Switzerland. Particularly the trend development is very helpful for early identification of possible faults. However the built-in gas interpretation schemes are usually not observed. As the monitors reliability may be limited due to service intervals, even defects and sometimes ill-conceived technology, all alarms of gas monitors are confirmed with laboratory DGA.

Bushing monitoring is installed in much fewer transformers. This might be due to the low accuracy of these systems and the limited price-for-value.

Partial discharge monitoring is applied only on a few units and still requires expert knowledge for corona separation and PD analysis.

3.5 Value of Furan Analysis

Furan analysis for estimating paper ageing is regularly applied to most generator step-up units and important substation transformers. Furan analysis is additionally applied after identification of a thermal fault to find out, if the fault is in paper or blank metal.

The authors consider the estimation of the degree of polymerisation based on furan concentration as questionable at least for non-breathing transformers. Figure 12 shows the decrease of the DP of paper (index P) and of board (index B) during an extended ageing experiment, which compares different insulation oils, [6]. The full lines give the direct measurement on material samples, while the dotted lines show the estimation based on furan content in oil. The lines of all different oils are here omitted, since the DP was similar for all samples though aged in different oils.

Ageing under presence of oxygen from air results in somewhat faster ageing. The DP of the pressboard samples exceeds that of the paper samples, though the temperatures where identical. Yet the most surprising finding is the similarity of all DP values independent from type of oil. On the other hand, the furan concentrations suggested big differences. Conclusively the furan concentration in oil seems to depend predominantly on the thermal stress and decomposition of the oil, but not on that of the paper. It is also remarkable that the agreement between furan-based DP estimation and real DP measurements is sufficient for the ageing under presence of air. In contrast to this, the ageing under absence of air leads to a big difference between the DP estimation and the real DP measurement. In the practical case of sealed power transformers this may lead to a significant underestimation of the ageing condition of the paper, if the user relies on the often applied relationships between furan content in oil and DP of paper.

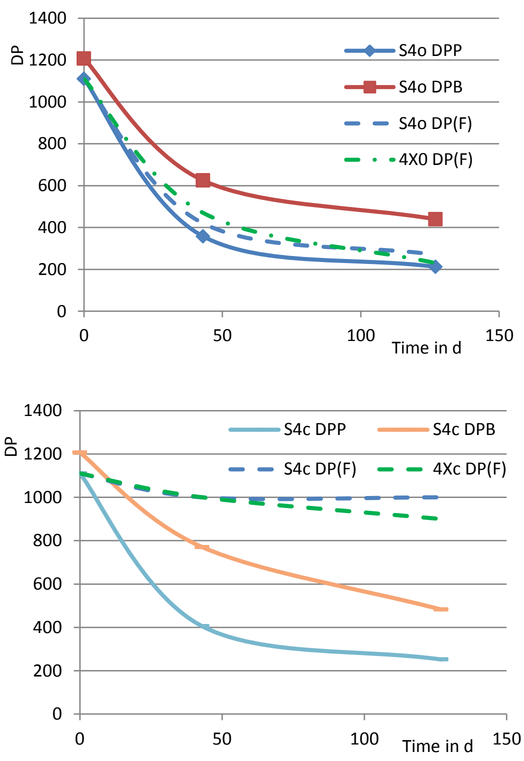


Figure 12: Degree of polymerization of paper (P) and transformer board (B) during ageing under the presence (above) and the absence of air (below). The full line gives the measurements on material samples, while the dotted line is the estimation based on furan content.

3.6 Most Frequent Faults in Instrument Transfomers

For instrument transformers, the most frequent fault is increased water content in oil. One possible reason are broken gaskets. In such cases sampling is repeated and then the unit replaced.

4 STATISTICAL SUMMARY AND CONCLUSIONS

Figure 13 displays the statistical evaluation of oil samples which do not meet the requirements of IEC 60422.

With 11.5 % of all oil samples the interfacial tension is the most frequent reason to fail the criteria of the standard. This is followed by water content in oil, where the value corrected to 20°C is used for evaluation. However, this parameter may be somewhat exaggerated as it is often influenced by poor sampling. The next parameter is then the neutralization number (total acidity), where 3.4 % of all oil samples fail. Only 1.5 % of the oil samples fail to meet the limits for dielectric dissipation factor and only 0.8 % these of breakdown voltage.

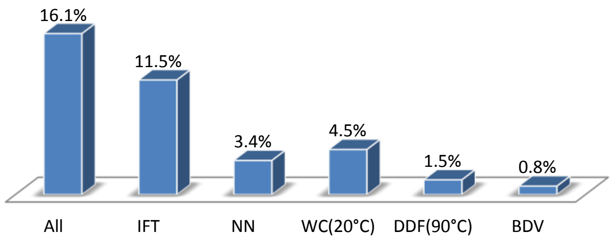


Figure 13: Percentage of oil samples in disagreement with the requirements of IEC 60422 and the contribution of individual measurement parameters

Figure 14 displays the statistical evaluation of all DGA samples giving indication of a possible fault; that is 8.9 % pointing on a thermal fault of 300-700°C and 6.1 % on partial discharges.

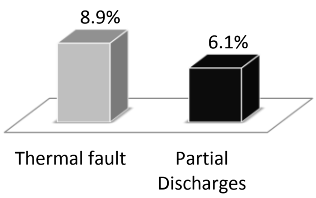


Figure 14: Percentage of DGA analyses with indication of a thermal fault or a partial discharge

From these evaluations and their experiences the authors would like to derive some conclusions.

Interfacial tension: With 11.5 % this parameter by far accounts for most of the negative indications. This is sometimes even not accompanied with other substantial signs of ageing. To the view of the authors the present requirement of IEC 60422 (20 resp. 22 mN/m) is too rigorous. Earlier versions of that standard had lower values, e.g. 15 mN/m (1989-04). The authors would like to propose to lower the present limit.

Water content: The use of water content in ppm (water mass to oil mass in µg/g), and this even without correction for the sampling temperature, as the present version of IEC 60422 prescribes, leads to a number of disadvantages. Without temperature correction no relationship exists to previous data of the same equipment. As oil ageing strongly increases the moisture solubility, no estimation of the moisture contamination of the transformer is possible. The authors would rather recommend using water saturation, which excludes the influence of oil ageing.

Dielectric Dissipation Factor: Because oils fail only after very severe ageing, the limits of the IEC 60422 seem to be too lax. Even under accelerated ageing tests in the laboratory these limits were never reached.

Breakdown Voltage: Breakdown voltage primarily depends on the moisture saturation in the liquid and, to a lesser extent, on particles in oil. Breakdown voltage is not related to oil ageing. The repeatability is low and the test result is only valid for a homogeneous electrode arrangement. Therefore a more realistic test method would be helpful for the industry.

Dissolved Gas Analysis: The authors made good experiences with DGA and the reliability of its predictions.

Furan Analysis: The authors are reluctant to apply the traditional relationships of 2FAL concentration to DP of paper; in particular for non-breathing transformers. Furan analysis is rather understood as a generic indicator of paper ageing with limited quantitative relationship to the DP in paper.

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