Transformer diagnostics: Common used and new methods

G. J. PUKEL[1], H. M. MUHR[1], W. LICK[1]

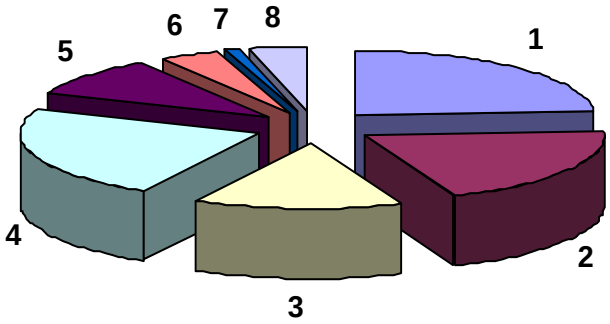
[1]Institute of High Voltage Engineering and System Management, Graz, University of Technology, Inffeldgasse 18, A-8010 Graz/Austria

***Abstract* — To receive the current isolation condition of a power transformer you have a large number of diagnostic methods available. A consistent picture results usually only from view of several indicators, on the basis of relevant standards and experiences as well as from trend analysis of different characteristics. In general the diagnostic methods deliver the status of power transformers and the prediction of the ageing condition. Ageing in the insulation system of power transformers is caused by impact of air, moisture, temperature, mechanical and electrical overstressing and insulation contamination.**

***Index Terms* — Diagnostic methods, oil analysis, dielectric diagnostic.**

I. INTRODUCTION

Transformers are one oft the most important and cost-intensive components of the electrical power supply. Therefore a big interest for significant diagnostic parameter exists. These parameters should represent the state of aging of the insulating components (board and oil) and they should also show incipient failures which can lead to a damage of the transformer. Figure 1 shows the typical failure distribution of high voltage transformers. It can be seen that the highest risk for a failure are the windings and the bushings of a transformer because in these regions the highest electrical field occurred during operation.



1 Windings	24 %
2 Core	20 %
3 Switching device	14 %
4 Bushings	23 %
5 Tank	10 %
6 Cooling system	4 %
7 Safety devices	1 %
8 Others	4 %

Figure 1: Failure distribution of high voltage transformers according [1]

Before a transformer starts running test were performed. These tests can be classified in routine tests, type tests and special tests. Routine tests are required for each transformer. Routine tests are resistance measurements, determination of the voltage ratio, loss measurements and also acceptance tests like partial discharge tests or voltage withstand tests for alternating voltage and impulse voltages before delivering the transformer to the user.

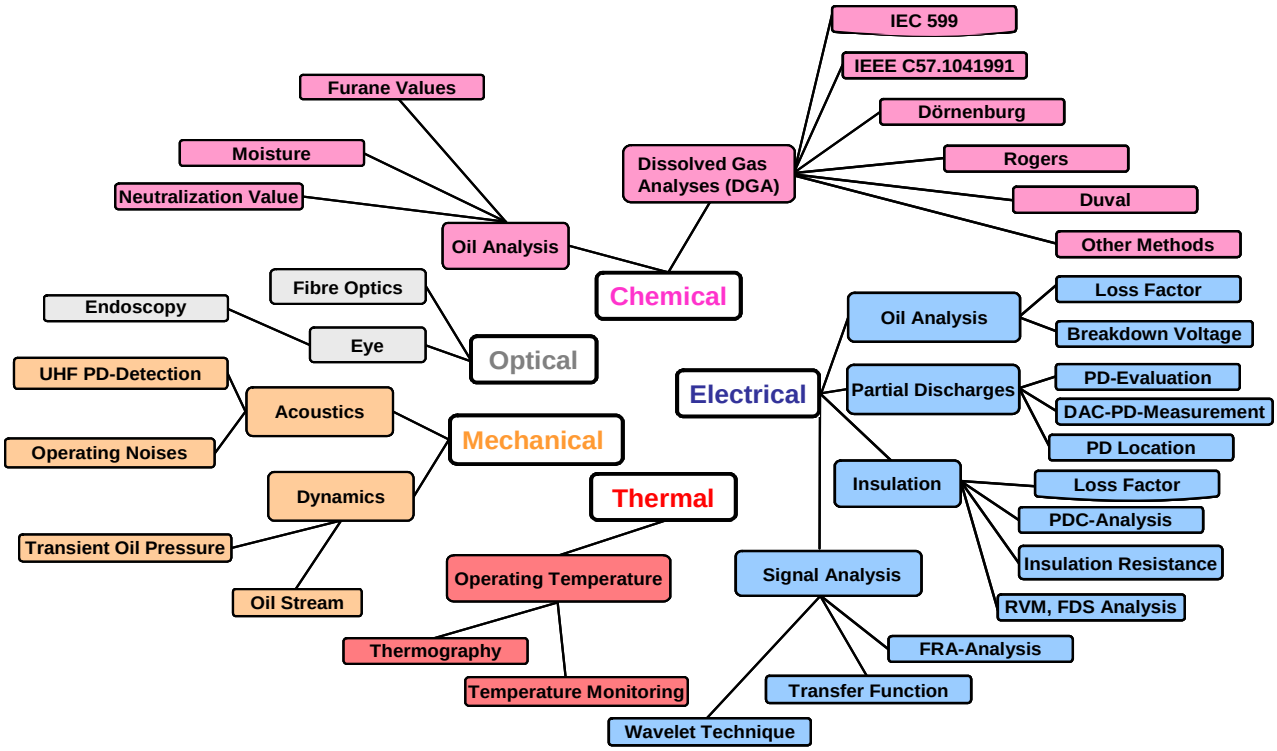
Type tests are tests which were performed only for each transformer design. These tests are necessary to show that the design fulfills defined criteria for instance a temperature rise test. And special tests are tests which were agreed between manufacturer and user. An example therefore are sound level tests. The acceptance criteria for special tests were defined between user and manufacturer. In the different standards there are acceptance criteria available only for routine tests which may be used. For instance the IEC recommended for partial discharge measurements of the whole transformer the following levels for the apparent charge:

- 500 pC at 150% U_m
- 300 pC at 130% U_m
- 100 pC at 110% U_m

Where U_m is the “highest voltage for equipment” according to IEC.

The most popular insulating system for transformer is the oil-board insulating system. The oil and the board are organic components and underlie aging., which depends highly to the operating conditions. Overload, transient overvoltages, disturbances of the cooling system accelerate the aging. A fast aging of the transformer insulation can also have electrical reasons, like partial discharges and local arcs, or chemical reasons such as catalytic processes and electrolysis.

To check the transformer condition during operation there are a lot of diagnostic methods available. Table I deliver an overview of common used methods.



Common used diagnostic methods are based on:

- Chemical diagnostic methods
- Electrical diagnostic methods
- Thermal diagnostic methods
- Optical diagnostic methods
- Mechanical diagnostic methods

II. CHEMICAL DIAGNOSTIC METHODS

Chemical methods become more important because of the development of new sensors with a higher sensitivity for collection of particles in the ppm (part per million) range. An important chemical method is the Dissolved Gas Analysis (DGA). It is the most efficient tool for the recognition and classification of thermal and electrical failures. Typical failures produces typical gases which were solved in the oil. Typical failures which can be recognized with the DGA are local oil breakdowns, overheating, partial discharges. Such failures produces hydrogen, oxygen, nitrogen and lower-molecular hydrocarbon compounds as methane, ethane, carbon monoxide or carbon dioxide. Very important is the extraction temperature of the oil because the solubility of the different gases in mineral oil depends heavily on the oil temperature. And also the extraction position has an big influence to the result. Figure 2 shows a significant difference for the total failure gas amount depending on the extraction position. Especially for methane (CH4) the is a difference up to 100% between a gas sample which was extracted from the bottom of the tank and the Buchholz protection device of the same transformer.

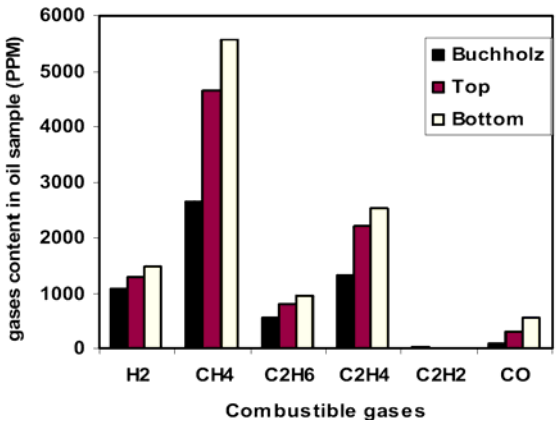


Figure 2: Total gas amount for different failure gases in dependence of the extraction position, according [2]

So the main problem is the determination of limit values for the single gases. How much gas gets produced depends on the transformer design, used materials and the stress condition. The evaluation of the measuring results can be performed according to different standards and methods. The most important are:

- IEEE C57.104-1991
- IEC 60599
- MSS-Schema
- Dörnenburg
- Rogers
- Duval

Usually not the absolute amount of the different failure gases are significant but the ratio of the gases.
Another important chemical oil analysis is the

determination of the oil humidity. Therefore usually the Karl-Fischer titration is used which is standardized in ASTM D1533-00 and IEC 60814. The electrical breakdown strength of oil depends highly to the amount of water in oil. Figure 3 shows a significant decrease of the oil breakdown strength when the water in oil is not in dilution.

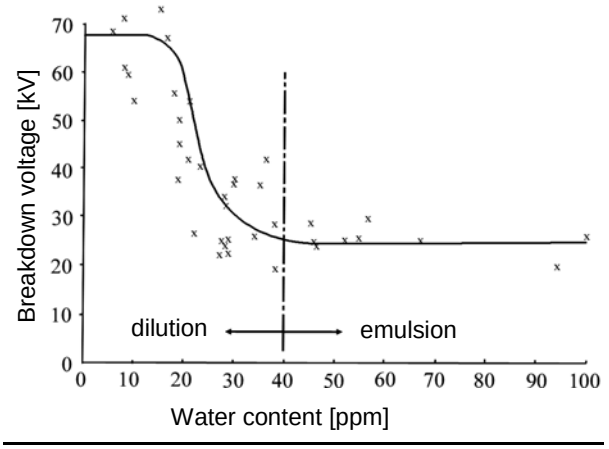


Figure 3: Breakdown voltage of oil versus water content according [3]

The water content of oil can also used for the determination of the paper humidity. There exist an correlation between the water content in oil and the water content in paper for the condition of equilibrium.
With Figure 4 (Piper -Chart) the paper humidity can be calculated with the measured oil humidity.

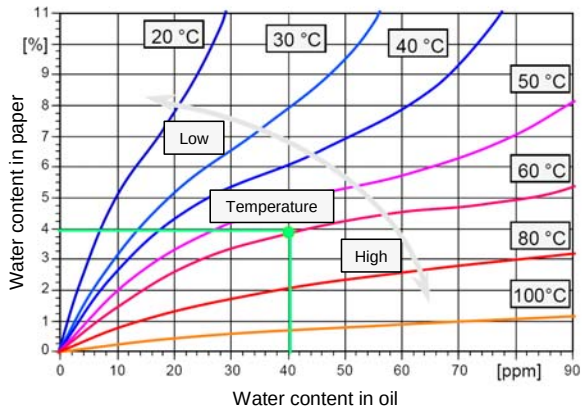


Figure 4: Piper-Chart (Nielsen –diagram) for a new oil according [4]

The calculation of the paper humidity with the help of the Piper-Chart is only valid for paper not for board or for synthetic resin board and also only for new oils available. A reliable method for determination of the paper humidity is the PDC-analysis, see chapter electrical diagnostic methods.
The analysis of paper samples give a direct statement about the characteristics of the solid isolation. A sampling is not “non-destructive” and usually very difficult. Furthermore this removal is often not representative because the paper samples can be taken only out of boundary regions and not in the closeness of the highly stressed regions. The complete and / or critical loss of the mechanical strength of cellulose fibers is shown at the length of the fibers, means recognizable from the average polymerization degree. An easier way to determine the condition of the solid insulation can be done with the help of the so called furan analysis. With this new method decomposition products of the paper which were absorbed from the oil were measured. The following decomposition products were generated and absorbed from the oil by aging of the paper: 2-furfural 2 FAL (Furfurol), 5-hydroxymethyl-2-furfural 5 HEF, 2-acetylfuran 2 ACF, 5-methyl-2-furfural 5 MEF, 2-furfurylalcohol 2 FOL. There exist a correlation between the degree of polymerization and the furfurol content, figure 5.

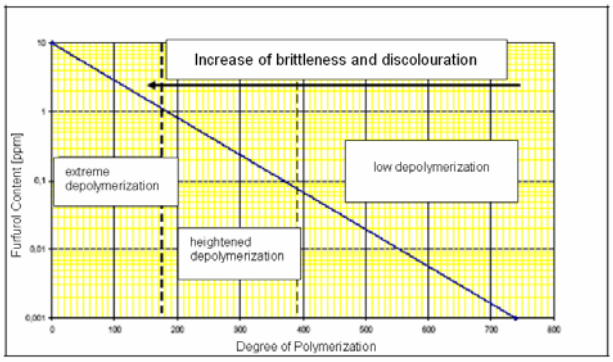


Figure 5: Degree of polymerization versus furfurol content according [5]

The same problem as mentioned for the DGA exist also for the furan analysis concerning the determination of a limit value. The total quantity of the produced furans in the oil sample depends on the oil temperature, oil type, type of paper, ratio oil/paper, moisture content and so on. So only the tendency of repeated measurements should be evaluated.
Other important chemical diagnostic methods, especially for determination the oil condition, are the investigation of the colour and appearance, acidity, neutralization value, interfacial tension, sludge content, particle count and corrosive sulphur.

III. ELECTRICAL DIAGNOSTIC METHODS

The most famous and popular electrical diagnostic method for evaluation of the oil condition is the oil breakdown voltage. This method is standardized and deliver as result the resistibility of the oil against alternating voltage. This resistibility is influenced basically from the water, particle and gas content of the oil. The aging condition of the oil can be evaluated by measuring the loss factor. Aging products in the oil increase significant the loss factor and also the specific resistivity.

The PDC (polarization and depolarization current) measurements become more and more importance for the determination of the insulation humidity. The results are more reliable than the calculation with the Piper-Chart. However necessary for the humidity determination is the acknowledgement of the dielectric parameters (R,C) of the test object. Figure 6 shows the interpretation of a PDC measurement of a transformer winding.

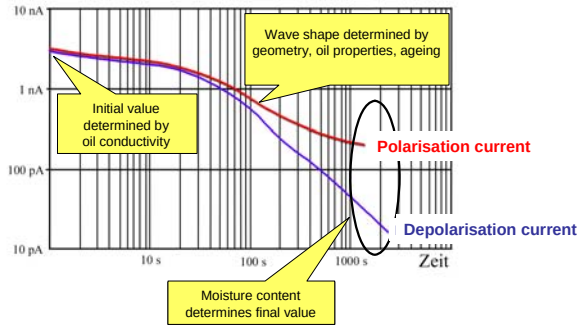


Figure 6: PDC measurement of a transformer winding according [6]

It is also possible to check the insulation humidity with the frequency domain spectroscopy (FDS) were frequencies between 0.001 up to 1000 Hz were applied to the insulation. The information lies in the phasing between voltage and current in dependence of the frequency. For inspecting mechanical deformation of a transformer (after a transportation or a short circuit) tests with transient test voltages make sense. Therefore the frequency response analysis (FRA) and the determination of the transfer function can be performed. Other electrical diagnostic methods by using transient voltages are the low voltage impulse response (LVI) and the wavelet analysis.

IV. THERMAL AND OPTICAL DIAGNOSTIC METHODS

Both thermal and optical diagnostic methods using the electromagnetic spectrum between 10^4 Hz up to 10^{16} Hz as information source. Either the transformer produces a signal which get detected (for instance heat produces infrared signals) or the transformer reflect signal (for instance surface temperature sensors which reflect high frequency impulses in dependence of the transformer temperature). Temperature monitoring can be performed with the help of PT-100 elements, by using fiber optics or thermography. The best optical diagnostic method is the human optical inspection for inner inspection with the help of the endoscopy.

V. MECHANICAL DIAGNOSTIC METHODS

The tension force of the transformer windings is important for the avoidance of deformation in the case of short-circuit. This tension force decrease during operation so a monitoring is useful for transformer where the risk of short-circuit is high. A possibility for determination of the existing tension force is the measuring of the transient oil pressure after applying of a current surge. The lower the tension force the higher transient oil pressure. Another mechanical diagnostic method is the stream analysis for controlling the cooling system. With this method also mechanical deformation in case of a short-circuit which influence the cooling system can be detected.

VI. CONCLUSION

For the transformer diagnostics there are many methods available. Oil analyses have a dominant meaning because of the simple availability of the oil samples. Dissolved Gas Analysis (DGA) deliver the most significant results whereas the determination of the breakdown voltage is the most popular diagnostic method. Furfural analysis get more and more importance for the diagnostic of the paper insulation also dielectric measurements like PDC. Thermal, optical and mechanical methods are additional methods which were used only for special cases.

VII. REFERENCES

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