TRANSFORMER CONDITION AND OPERATIONAL RISK EVALUATION

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Abstract: In this joint project between five companies and two universities an algorithm for the evaluation of the condition and operational risk of aged power transformers was developed. In the first stage the operational dates and results of oil analysis investigations as well as maintenance measures of about 70 selected transformers were collected in a standardized scheme. These data were the basis for the further analysis of the technical condition. The oil analysis results according to IEC 60422 (chemical physical parameters) as well as IEC 60599 (dissolved gas analysis) were evaluated and interpreted automatically.

In a second stage a diagnosis program for onsite measurements at most of the selected transformers was developed. For the diagnosis of the solid insulation system the winding resistance and winding insulation was measured and the polarization and depolarization current (PDC), frequency domain spectroscopy (FDS) and frequency response analysis (FRA) was applied. The tap changer and the bushings were tested with a resonance system. At the tank a visual inspection was done. At some transformers actual oil samples were taken and analysed by chemical parameters, DGA and furan analysis. All diagnosis and test results were evaluated and collected in the evaluation algorithm.

At one transformer an end of life inspection was done in the site of a transformer manufacturer after a full diagnostic program onsite. The results of the diagnostic measurement onsite and the results of the inspection after opening the transformer corresponded excellent.

The developed algorithm enables a view to the condition of each transformer and a comparison of the whole fleet. The operational risk of each transformer component is evaluated by bar graphs. If there were any critical components found recommendations for maintenance measures were worked out. The aim of this algorithm was to collect the operational history with the focus to find the actual condition and the operational risk of each transformer.

1 INTRODUCTION

Power Transformers are critical and capital-intensive assets for utilities and industry. Due to the increasing pressure to reduce costs, the utilities and industry is forced to keep old power transformers in operation as long as possible. With the advancing age of transformers it is very important to know the condition of the transformer. The evaluation of the reliability of power transformers is essential.

A set of modern diagnostic methods is available and applied for oil filled power transformers. Defects in transformers can be caused by mechanical, thermal and dielectric stresses either individually or in conjunction. It must be taken into account that the majority of the diagnostic methods are sensitive to all three fundamental stresses acting on the transformer. Therefore, the general interpretations including the localization of faults can be problematic. The experience and interpretation capabilities of transformer experts are crucial for a successful diagnosis.

Depending on the diagnostic method the measurements will be arranged during operation or during short time de-energization (usually several hours). If any extensive fault was located by the diagnosis measurements the failed unit is normally transported to the repair workshop where the required space and equipment is available. Also the cost and risk of such a heavy transport has to be considered. For the save operation of power transformers the maintenance strategy is significant. Within this project the results of diagnostic measurements in different utilities and companies were investigated and strategic measurements to determine the condition power transformers were applied. The focus was laid on service aged power transformers.

2 MAINTENANCE MEASURES AND DIAGNOSTIC MEASUREMENTS

2.1 Maintenance, Visual Inspection

Within the normal maintenance program the transformers were inspected visual by the engineers of the utility. Following parts of the transformer were inspected:

- Top oil temperature and the winding temperature
- Oil level gauge on the conservator (main tank and OLTC compartment) and OIP bushings, if present
- Dehydrating breather
- Entire transformer for oil leaks
- Fans and radiators
- Buchholz relay
- Gauges, bushings, surge arresters, conductor connections, grounding
- Corrosion protection a tank condition
- Thermography by infrared camera to detect thermal problems

2.2 Diagnostic Measurements

The most important diagnostic tool is the oil analysis, where the chemical physical parameters (CPA) as well as the dissolved gases in oil (DGA) were analysed. The oil analysis is described in the standards IEC 60422 and 60599 and enables to classify the quality of oil and cellulose and to detect special types of failures in the insulation system.

Additional to these two standard investigations the condition of paper can be investigated by the furan analysis according to EN 61198. Cellulose materials, such as paper and pressboard are composed of polymerized glucose molecules. This molecules break up into smaller chains which depends on the temperature, moisture content, oxygen and acids in the insulation system. Chemical products such as furanic derivates are produced and dissolve in the transformer oil. Labs usually report five different furanic compounds, but for diagnosis purposes only 2-furfuraldehyde (2FAL) is considered. The concentration of 2FAL in transformer oil and the degree of polymerisation (DP) value of the cellulose materials are correlated to each other. This can be used as an indicator for degradation of solid insulation. New paper (after drying and impregnation) has a DP value in the range of 800 -1000. When it reaches a value of 200 it is generally considered that the transformer has reached the end of life. The transformer will not withstand short circuit forces anymore.

Figure 1: Extraction of a cellulose sample at the connection of the transformer bushings [1]

Beside the chemical and physical properties of the insulation system also electrical and dielectrical parameters were investigated to determine the condition and operational risk of the investigated aged transformers. Following electrical tests were applied:

Static resistance measurement: A static resistance measurement onsite is used to check the contacts condition (Tap changer, bushings) as well as winding short circuits and disconnections. The static winding resistance test will be performed for all three phases and tap positions. In Figure 2 the unsteady resistance changes around the middle tap position and in the tap positions 4 and 18 is shown. This indicates an increase of the contact resistance of the tap selector. The deviations between switching upwards (UP) and switching downwards (DOWN) are also significant for an increase of the contact resistance.

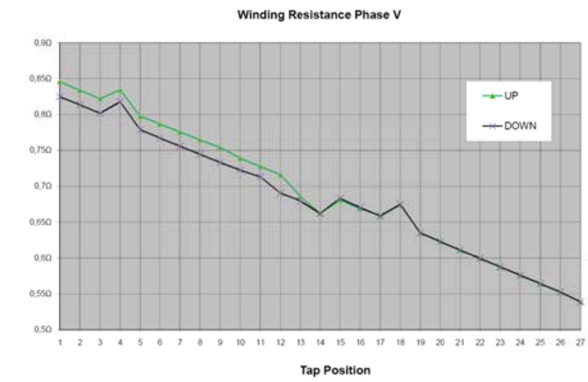

Figure 2: Example of a winding resistance test with the result of increased contact resistance [2]

Dynamic resistance measurement: With a dynamic resistance measurement, the dynamic behaviour of the diverter switch can be analysed. The process of tap changing from one tap to the next one:

- Diverter switch commutes from the first tap to the first commutating resistor
- The second commutation resistor is switched parallel
- Commutation from the second commutation resistor to the second tap

This measurement is used to check whether the on load tap changer OLTC switches without interruption. A properly working tap change differs from a malfunctioning one, for example, an interruption during the change, by the magnitude of the ripple and slope values. An interruption will result in much higher ripple and slope values than a regular functioning tap change.

Additional the **Transformer Ratio** and a **Partial Discharge Measurement** (acc. IEC 60270 and UHF) were applied but should not be described further on in this paper.

Following **Dielectric** parameters were tested at the transformers:

- **Capacitance and Dissipation Factor** of the active part
- **Insulation Resistance (IR)** of the winding insulation between the HV winding and tank as well as between HV and LV/MV windings
- **Dielectric Response** of the whole insulation system to determine the moisture in cellulose by **FDS** and/or **PDC** method

An example of the IR evaluation is pointed out in Fig. 3. The IR can vary due the moisture content, impurity content and the temperature of the insulation parts. All measurements are corrected to 20°C for comparison purposes. The result distinguishes the quality of oil and general insulation condition.

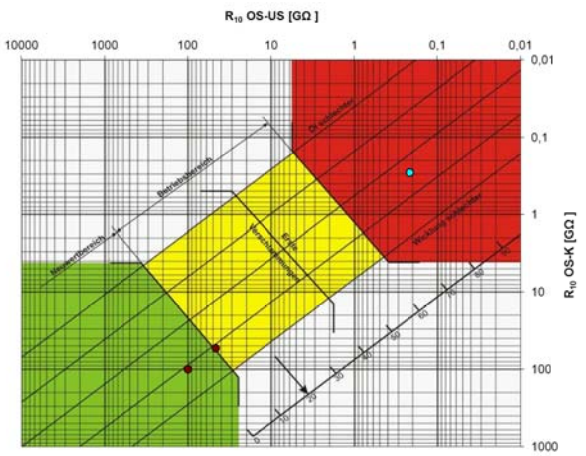

Figure 3: Evaluation of the **Insulation Resistance** measurement [3]

Additionally at the bushings the capacitance and dissipation factor in frequency domain were measured.

3 POST MORTEM INVESTIGATION AT A POWER TRANSFORMER

At a 40 year old 20MVA 110/21/10,5kV transformer a full diagnostic program was applied onsite. This transformer showed a high content of ethane during the last years of operation. To eliminate this problem a revision of the on-load tap-changer was done.

The transformer was transported to a workshop where it was finally tested and disassembled. At these final tests the oil analysis showed a high content of water and acidity as well as a low level of the interfacial tension so that the mineral oil has to be classified as aged. The DGA showed normal behaviour, the operational risk was classified as normal. Also at the furan analysis a normal paper condition was determined. The dielectric measurement of the paper insulation (FDS and PDC) brought a dry condition (1.5% humidity in paper). At the FRA analysis no deformations could be detected. The diagnostic measurements of the OLTC showed normal mechanical and electrical behaviour only a beginning degradation of the contacts was detected. The partial discharges were measured at several points of the tank by acoustic sensors; a hot spot at the top of the core in the area of a coil support could be detected. Finally the pressing force of the windings was tested with the vibration analysis method; a degradation of the mechanical pressing forces could be detected.

Table 1: Results of Onsite Testing and Disassembling in the Transformer Workshop

Onsite Tests	*Tests at disassembling*	*Remarks*
Reduced pressing forces detected	Reduced pressing forces confirmed by visual inspection of pressing appliance	The correct pressing forces could be restored by revision
PD detected by acoustic sensors	Discharge tracks from PDs detected by visual inspection at core appliance	Constructive deficiency, can be eleminated
Humidity of paper 1.5% assessed (FDS)	Paper humidity measured at 4 samples: about 2%	Raising humidity in paper after opening of transformer possible
Raised winding resistance due to contact degradation of OLTC	Coking at OLTC contacts detected at visual inspection	Revision of OLTC onsite possible
Furan analysis sowed normal degradation of paper	DP value of 4 paper samples tested: 500 … 700 DP condition normal aged	Paper condition: normal aged, no immediate risk

Figure 4: Results of Visual Inspection at Transformer Disassembling: PDs at core locking device (up) and reduced pressing force at winding (down)

4 COMPREHENSIVE EVALUATION ALGORITHM

The developed algorithm consists of different modules. Within each module a condition factor is calculated. All condition factors were weighed according to the importance and expressiveness to the transformer condition.

Within the oil module the results of the CPA methods as well as an interpretation of DGA are done. For the interpretation of the test results the well-known standards of IEC and IEEE give the basis. The results of the CPA were summarized to a factor by building an average value of all tests. The reason is that each parameter can be improved by suitable measures. The analysis results have to be interpreted schematically in a specific sequence according to figure 5 and [4]. If one of each tested parameter is in the overhaul or danger area measures have to be applied to improve the oil quality to the normal operation area.

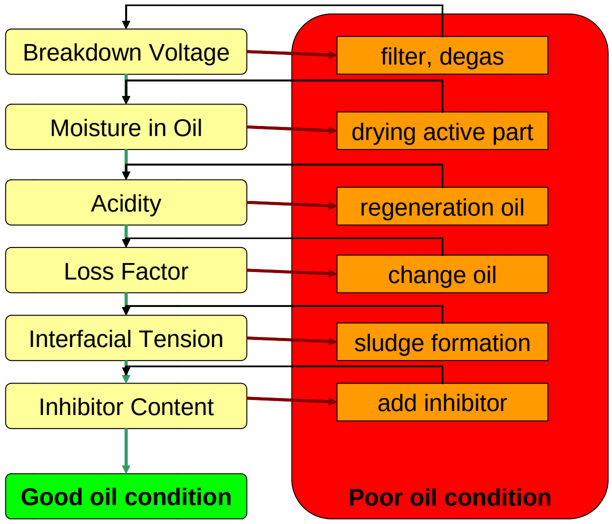

Figure 5: Oil Analysis Module CPA

The second module for the oil evaluation refers to the interpretation of the DGA. With the DGA different faults in the insulation system of the transformer can be identified: thermal failures, discharges or partial discharges. To detect these failures different schemes were applied: Dörnenburg, Rogers, Duval, MSS, IEEE (quotient criteria, ratio method) and IEC (total dissolved combustible gases).

The worst result of all DGA schemes builds the final condition factor in this module. The reason is that it can happen that not each schema results in an expressive result. And finally the result of the insulation resistance measurement is a part of the evaluation. The schematic strategy to determine the DGA condition factor is shown in figure 6.

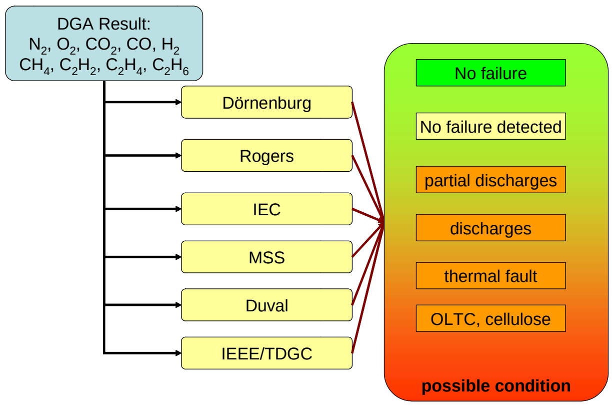

Figure 6: Oil Analysis Module DGA

The module for the evaluation of the paper condition consists of following tests, which should be applied sequentially, see figure 7. Normally the moisture of oil is tested by the oil module CPA. It is important to record the oil temperature during tapping. With equilibrium curves the moisture content of the cellulose can be determined. A second parameter is the ratio of CO_2 to CO from DGA. It can be distinguished if the paper is normal, aged from electrical or thermal exposition. Additionally the insulation resistance (IR) between HV bushings and tank as well as between HV and MV bushings gives information about the condition of oil and paper between the windings. The moisture in paper can be measured in a good accuracy by dielectric methods of FDS or PDC. For the dielectric measurements the transformer has to be disconnected from the grid. The furans can be additionally measured from the oil samples by HPLC equipment. The 2FAL is an integral value over the whole insulation system, for this reason it gives an average condition over the paper strength. To determine the residual paper strength at critical parts of the insulation system paper samples have to be extracted by dissembling the active part of the transformer. This procedure is very expensive and therefore applied only in rare cases.

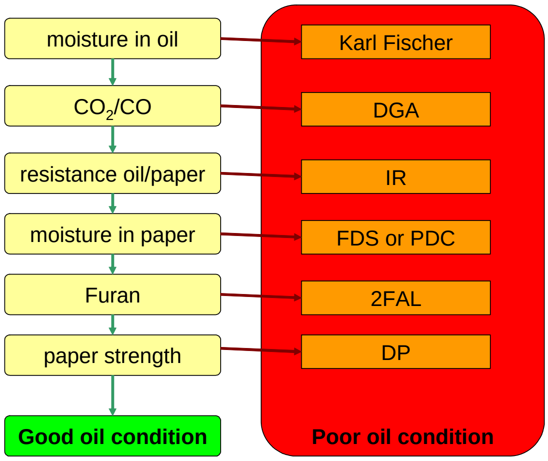

Figure 7: Paper Analysis module

The module for the evaluation of the other transformer components consists of the bushing, load tap changer and tank observation, as shown in figure 8. Basis was the operational dates of this equipment: e.g. age, type of construction, used insulation materials, duration of exposition, general condition, results from visual inspection. Additionally results from diagnostic measurements were collected and evaluated. For example at the bushings the loss factor over frequency is measured to detect moisture in the insulation system or the capacitance to find short circuits between layers. At OLTC the dynamic resistance, the contact resistance and the switching intervals were measured during the inspection.

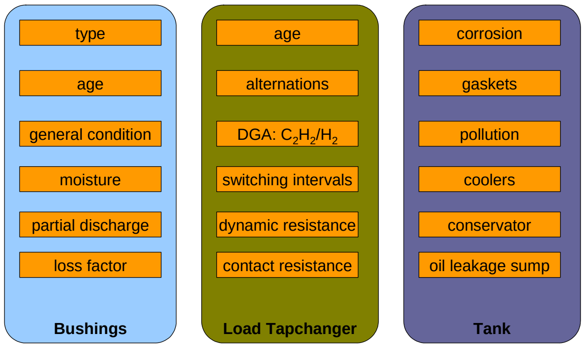

Figure 8: Transformer Components Analysis Module

5 EVALUATION OF TRANSFORMER COMPONENTS AND RISK ASSESSMENT

For the analysis of the transformer components oil, paper, bushings, OLTC and tank benchmarks were calculated from described modules. In recent publications this procedure is described as health index method [5-9]. In this project the condition spectrum varies between following marks: an excellent (new) condition is described by one, a good condition with two, service aged by three, a poor condition by four and an unsatisfactory condition with five. Each benchmark consists of several parameters. As example the oil condition is determined by the results of oil module CPA and DGA as well as the insulation resistance measurement.

One example of an evaluation is shown in figure 9, where the oil is in a service aged, the paper in a good condition. The bushings were ok but aged, the OLTC is also aged but shows no defects and finally the tank has to be serviced due to high pollution and light degree of corrosion. The operational risk of this transformer is classified medium, this means that this transformer has a save operation up to the next service interval, but it is recommended to apply oil analysis in a minimum of one year for the DGA and three years for the CPA. The paper shows now aging. The oil has light lacks due to a high content of moisture. By drying the oil this defect can be eliminated with small expenses. Finally it can be summarized that this transformer can be operated the next 3 to 5 years with a low risk of insulation failure and probability of an outage.

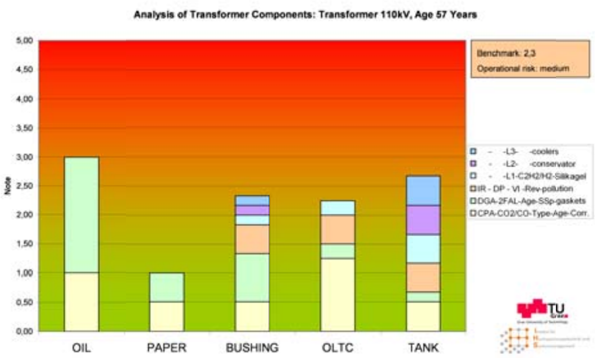

Figure 9: Condition of Transformer Components

6 CONCLUSION

In this paper the idea of the comprehensive condition evaluation for power transformers were discussed and presented. At first different diagnostic measurements were applied and the expressiveness of each method discussed. Then the operational dates of the investigated transformers were collected in a data base, which was used for the evaluation algorithm. The criterions for the condition assessment were derived from standards and state of the art recommendations. In a further step the results of diagnostic measurements and visual inspection were acquired to the same data base. Finally the condition of the transformer components and a risk analysis is set up on this data base.

The post mortem investigations showed that the dielectric measurements which were done before the dissection of the whole transformer and the result of the evaluation algorithm correlated very satisfactory.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] … [3] Transformer Test Reports of Kelag Netz Gmbh

[4] I. Höhlein, A.J. Kachler, H. Lütke, U. Theiß: „Transformer Life Management“, Brochure Siemens AG Nürnberg, Bestell-Nr: E50001-U410-A34

[5] M. Ahfaz Khan, A.K. Sharma and R. Saxena, "Expert System for Power Transformer Condition Monitoring and Diagnosis", International Conference on Power Electronics, Drives and Energy Systems, PEDES '06, pp. 1-6, 2006

[6] D. Arvind, S. Khushdeep and K. Deepak, "Condition monitoring of power transformer: A review", T&D. IEEE/PES Transmission and Distribution Conference and Expositio, pp. 1-6, 2008

[7] V. Rusov and S. Zhivodernikov, "Transformer condition monitoring", International Conference on Condition Monitoring and Diagnosis, CMD 2008, pp. 1012-1014, 2008

[8] B. Sparling, J. Aubin, “Determination of Health Index for Ageing Transformers in View of Substations Asset Optimazation”, International Conference on Condition Monitoring and Diagnosis, CMD 2010, pp. 73-77, 2010

[9] C. Sumereder, „Analyse und Bewertung von Betriebsmitteln in der Hochspannungstechnik“, Habilitation Thesis, TU Graz 2010, ISBN 978-3-85133-058-8