DIAGNOSTIC MEASUREMENTS FOR THE CONDITION EVALUATION OF POWER TRANSFORMERS

Christof SUMEREDER
TU Graz - Austria
sumereder@tugraz.at

Stefan KORNHUBER
Doble Lemke - Germany
kornhuber@doble-lemke.eu

Roland SCHMID
VOEST ALPINE - Austria
roland.schmid@voestalpine.com

Gerd VALTIN
HTWK Leipzig - Germany
gerd.valtin@fbeit.htwk-leipzig.de

Torsten FRIEDRICH
ENSO - Germany
torsten.friedrich@enso.de

Martin AMMER
OMV - Austria
martin.ammer@omv.com

Michael MARKETZ
Kelag - Austria
michael.marketz@kelag.at

Matthias BOLTZE
Doble Lemke - Germany
boltze@doble-lemke.eu

Hermann FILIPOT
Kelag Netz GmbH - Austria
hermann.filipot@kelagnetz.at

ABSTRACT

Selected results of a project for the condition evaluation of power transformers were presented and discussed in this paper. In the first part the state of the art for power transformer testing and methods for diagnostic investigations and condition evaluation were investigated. The special interest for the further risk analysis and practical investigations were aged transformers. For this reason the operational data and historical results of oil analysis were collected in a standardized data schema. This data set was taken for a correlation analysis, where all available oil parameters of the chemical physical analysis according to the standard IEC 60422 and dissolved gas analysis (DGA) according to the IEC 60599 as well as furans were compared and significant correlations were investigated.

For the onsite measurements several aged power transformers were selected and extensive diagnostic measurements were applied. The solid insulation was tested by winding resistance, winding insulation, polarization and depolarization current (PDC), frequency domain spectroscopy (FDS), frequency response analysis (FRA), the tap changer was tested as well as the bushings and the tank by visual inspection. At some transformers actual oil samples were taken and analyzed by chemical parameters, DGA and furan analysis. All the test results were evaluated under the aspect to determine the condition of the whole transformer system and to detect weak components of the investigated transformer. At one transformer an end of life inspection was done in the manufacturer site. The results of the diagnostic measurement onsite and the results of the inspection after opening the transformer corresponded excellent.

The test results were collected in a data set which is the basis for an algorithm to compare the transformer fleet in an utility. The aim of this algorithm is to get the benchmarks of each transformer, to create a health index and finally to optimize the maintenance strategy. This algorithm was programmed in a standard calculation program and its aim was to guide the user with commends and recommendations for maintenance measures. It consists of different modules, the oil module with the focus on the evaluation of the mineral oil condition, the visual inspection module, the insulation resistance module, the module for risk assessment and finally the benchmark module where the transformer fleet is observed.

DIAGNOSTIC ONSITE MEASUREMENTS AT AGED POWER TRANSFORMERS

For the onsite measurements a set of 42 aged transformers at different utilities and an industrial company were selected. Under these transformers there were generator step up, network transformer and industry transformers. At all transformers a DGA, chemical physical oil analysis and furan derivates were determined.

Following electrical measurements were applied: Insulation Resistance, FDS and PDC analysis for the determination of the humidity in cellulose, FRA for the detection of winding displacements and partial discharge diagnostic and test of the OLTC.

Figure 1: Transformer Onsite Measurement

CORRELATION ANALYSIS OF DIAGNOSTIC PARAMETERS

The initial point is a series of diagnosis parameters which can be analysed in the course of oil analysis. Therefore, the recommended limits can be found in the standards. For each parameter, a special analytical method is required which causes the corresponding costs. If a company owns a noteworthy number of transformers, there is no doubt about the importance of accruing costs. Regarding the costs - it must also be taken into account - that the transformers should be analysed regularly. This leads to the requirement of a meaningful choice of the possible parameters. A further point of view is the range of occurrence of the analysed parameters which is part per million. The whole logistic chain consisting of the oil tapping from the transformer, the transportation to the laboratory and the analysis in the laboratory itself can be subject to undesirable influences which falsify the result. For purposes of estimation, if there is no contradiction in terms in the results, the knowledge of the dependences from one parameter to the others is helpful.

In [1] a helpful tool for supporting the choice of parameters for analysis is the determination of magnitude of the coherence between the different parameters with correlation analysis was investigated earlier. Together with the correlation analysis a quantification of dependencies of different parameters is delivered. Due to quantification of dependences an estimation is possible, if the compared values of the parameters are physically meaningful or the values are inconsistent because of undesired influences. The correlation analysis is based on the following considerations:

Correlations are a statistical method to measure a dependency between two or more variables [2]. These dependencies between variables cannot be used for interpretation in the sense of a causal relationship, because of correlative dependencies between variables potentially influenced (causal) from other variables. For checking the closeness of the connection with correlation there are at least two observed characteristics necessary which are collected as pair of values per investigation object (for example transformers).

A correlation where every investigation unit i is attached with a value x_i and y_i is identified with three substantial characteristics:

1.) Direction of dependency

Correlation can be classified into three classes, in positive, in negative and in zero correlation. With the positive correlation, both values tend to go in the same direction. With the negative correlation both values tend to follow the contrary direction. If there is zero correlation between both variables, there is no systematic dependency in any direction.

2.) Profile of dependency

The most frequent application of correlation is applied to linear dependency where the particular points in the scatter diagram tend to build a straight line. With another profile, a non linear dependency, the particular points in the scatter diagram tend to build a curve.

3.) Degree of dependency

Finally, correlation measures how well data fit with the corresponding profile. For example, a linear correlation measures how well the data fit to a straight line. A perfect correlation is identified through a correlation of ± 1, while a correlation of 0 suggests that there is no dependency. With values in between the approaching degree is shown from the data to a perfect straight line.

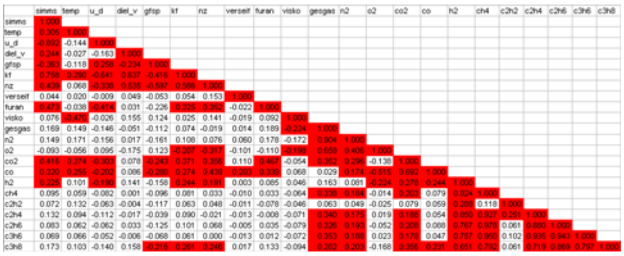
A measure developed for characterising dependencies is named Pearson Correlation. The Pearson Product Moment correlation is designated with the correlation coefficient r, and it measures the degree and direction of linear relationship between two variables.

The Pearson correlation is a conceptual result of:

$$r = \frac{COV(x, y)}{\sigma_x \sigma_y}$$

with: COV … covariance of variables x and y
$\sigma_{x, y}$ … standard deviation of x and y

Oil samples on 225 transformers were taken and the corresponding parameters were analysed. As the transformers were selected randomly, there were different types with different loads, and there was a higher scatter expected, which means a lower detected dependency. This signifies a lower correlation coefficient in comparison to samples taken from one and the same transformer 225 times during its lifetime. This method was chosen deliberately, because also in reality there are different transformers to analyse. For the investigation, if the parameters were actually interdependent, correlation was carried out with a significance of 0.01.



	simms	temp	u_d	diel_v	gfsp	kf	nz	verseif	furan	visko	gesgas	n2	o2	co2	co	h2	ch4	c2h2	c2h4	c2h6	c3h6	c3h8
simms	1.000																					
temp	0.305	1.000																				
u_d	-0.692	-0.144	1.000																			
diel_v	0.244	-0.027	-0.163	1.000																		
gfsp	-0.363	-0.118	0.258	-0.234	1.000																	
kf	0.758	0.290	-0.641	0.637	-0.416	1.000																
nz	0.439	0.068	-0.338	0.535	-0.597	0.586	1.000															
verseif	0.044	0.020	-0.009	0.049	-0.053	0.054	0.153	1.000														
furan	0.473	-0.038	-0.414	0.031	-0.226	0.325	0.352	-0.022	1.000													
visko	0.076	-0.470	-0.026	0.155	0.124	0.025	0.141	-0.019	0.092	1.000												
gesgas	0.169	0.149	-0.146	-0.051	-0.112	0.074	-0.019	0.014	0.189	-0.224	1.000											
n2	0.149	0.171	-0.156	0.017	-0.161	0.108	0.076	0.060	0.178	-0.172	0.904	1.000										
o2	-0.093	-0.056	0.095	-0.175	0.123	-0.207	-0.317	-0.101	-0.110	-0.198	0.659	0.406	1.000									
co2	0.416	0.274	-0.303	0.078	-0.243	0.371	0.356	0.110	0.467	-0.054	0.352	0.296	-0.138	1.000								
co	0.320	0.255	-0.202	0.086	-0.280	0.274	0.439	0.203	0.339	0.068	0.029	0.174	-0.515	0.692	1.000							
h2	0.225	0.101	-0.190	0.141	-0.158	0.244	0.191	0.003	0.085	0.046	0.163	0.081	-0.224	0.278	0.244	1.000						
ch4	0.095	0.059	-0.082	0.001	-0.096	0.081	0.033	-0.010	0.033	-0.064	0.338	0.184	-0.014	0.203	0.079	0.824	1.000					
c2h2	0.072	0.132	-0.063	-0.004	-0.117	0.063	0.048	-0.011	-0.078	-0.046	0.063	0.049	-0.025	0.079	0.059	0.288	0.118	1.000				
c2h4	0.132	0.094	-0.112	-0.017	-0.039	0.090	-0.021	-0.013	-0.008	-0.071	0.340	0.175	0.019	0.188	0.054	0.850	0.927	0.251	1.000			
c2h6	0.083	0.062	-0.062	0.033	-0.125	0.101	0.068	-0.005	0.035	-0.079	0.326	0.193	-0.052	0.208	0.088	0.767	0.978	0.061	0.880	1.000		
c3h6	0.069	0.066	-0.052	-0.006	-0.068	0.061	0.000	-0.013	0.012	-0.072	0.353	0.188	0.023	0.178	0.047	0.757	0.950	0.102	0.935	0.943	1.000	
c3h8	0.173	0.103	-0.140	0.158	-0.216	0.261	0.246	0.017	0.133	-0.094	0.282	0.203	-0.168	0.356	0.231	0.651	0.792	0.061	0.719	0.869	0.797	1.000

Figure 2: Results of Correlation Analysis

From the result of the correlation analysis 3 examples should be mentioned:

A strongly inverse dependency was shown between the moisture of oil, measured with the method of Karl Fischer, and the breakdown voltage with a correlation coefficient of -0.641.

In the same way, a strongly inverse dependency between the moisture of oil, measured with a capacitive sensor and the break down voltage with a correlation coefficient of -0.692 was shown.

The dependency between the acid number and the interfacial density also was shown as a strongly inverse dependency with a correlation coefficient of -0.597.

ALGORITHM FOR THE COMPREHENSIVE CONDITION EVALUATION OF POWER TRANSFORMERS

In several publications [3-6] the condition evaluation by the means of diagnostics were published. Normally the chemical and physical parameters of transformer oil as well as the dissolved gas analysis are the basis for the interpretation and determination of possible failures in the transformer. This way of condition evaluation is proven but in the case of weak parts at the transformer accessories possible failures may keep undetected. As example a bushing defect can not be detected by oil analysis and therefore some transformers burned down because of undetected bushing defects. A total loss of the power transformer with the high consequential damages occurred attended with high costs for not delivered energy and the replacement of the lost transformer unit.

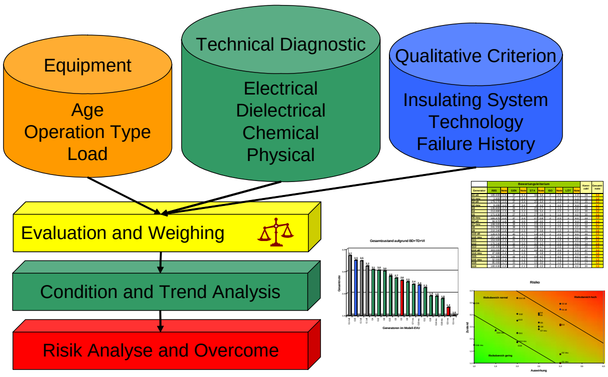


Figure 3: Comprehensive Condition Evaluation and Risk Management

At this place the idea of the comprehensive condition evaluation should be applied in this research project [7]. The strategy is to collect the results of operational dates, diagnostic results and so called qualitative parameters in the form of tables. Characteristic benchmarks should enable an objective comparison of all investigated transformer units and on this basis a qualification of the insulation system and the most important transformer components is possible.

For the quantification of the mineral oil condition the standards for DGA (IEC 60599) as well the schemes for the interpretation of failures according to IEEE Std. 57.104-2008 were solved within a fault tree analysis. The rating for the oil condition was done by the worst detected failure, e.g. if there were discharge with high intensity detected the evaluation was worse because the risk for further aging of the oil is high.

The second parameters for the oil evaluation were the results according to IEC 60422 and the schematic process according to [8]. If any observed parameter is in the overhaul area a poor and if the danger area was detected a bad condition is qualified.

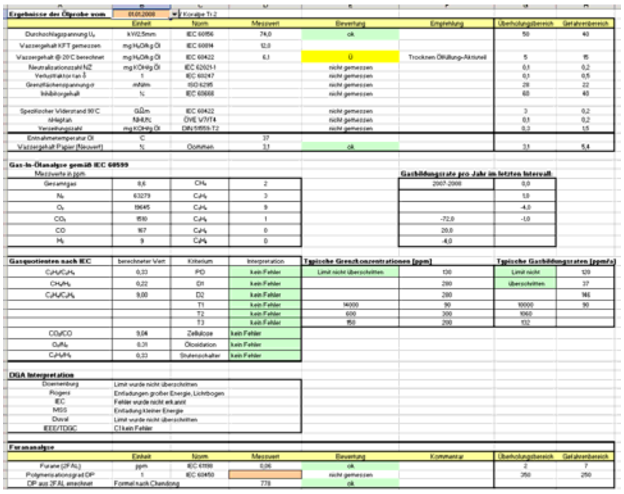


Figure 4: Analysis Tool for Oil Evaluation

Beside the easy to evaluate oil also the solid insulation in the transformer has to be scored. Recently the furan derivates (2FAL) which can easily determined by oil tapping, is a well proven method for the condition of the cellulose in the transformer. The constraint of this method is that the 2FAL value is an average value of the whole paper in the transformer and the mathematical transformation to the DP value. In this algorithm the formula according to Chengdong was applied. A more reliable but much more expensive method is the extraction of cellulose out of the transformer and the direct analysis and determination of the DP value. In the end also the results of 2FAL and DP were evaluated according to overhaul and danger area.

The next parameter for the evaluation of the cellulose is the content of water and also the ratio of CO_2 to CO. The first parameter can be determined indirectly from the humidity in oil and the equilibrium curves according [9, 10] or by measurement with a dielectric response method [11, 12]. The constraint for the first method is that the published curves were only applicable for new oil and new paper. The dielectric methods can only be applied offline.

At the active part following diagnostic measurements were applied and evaluated: IR of the winding, FRA for detection of winding expositions and PD according to IEC 60076-3 and IEC 60270 for the detection of any internal failures. The PD measurement was done broadband at 2.4MHz and narrow band at 200kHz as well as a 3FREQ record at a bandwidth of 650kHz between 200kHz up to 6MHz.

Finally the general condition of the transformer components was evaluated by visual inspection as well as by diagnostic measurements. The bushings were measured by FDS and the OLTC by dynamic resistance measurement and DGA.

An example for the evaluation of the transformer components is shown in figure 5. Benchmarks for the components oil, paper, bushings, OLTC and the tank were calculated within the algorithm. The results were shown as bar graphs with one as best and 5 as worst condition. In the shown example the transformer has a medium condition while the paper is in a quite fair state. So it could be recommended to do an oil regeneration (drying) and an overhaul of the tank as well as the OLTC. It has to be considered if the old RBP bushings were replaced by new RIP.

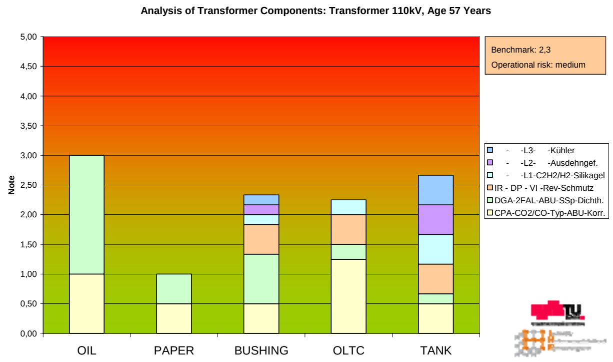


Figure 5: Evaluation of Transformer Components

SUMMARY

In this paper different methods for the evaluation of the transformer components by diagnostic tools as well as by visual inspection and analysis of operational dates was demonstrated.

The expressiveness of different oil parameters and their interrelation was investigated by the statistical mathematical method of the Pearson correlation analysis.

Finally the method of comprehensive correlation analysis was demonstrated and selected results of the new developed evaluation algorithm were shown. In this way weak components of a transformer can be detected more efficient and the results can be used for a risk analysis. Future investigations could implement the test results of different diagnostic measurements automatically.

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