EOL Conditions in Transformers

+ PoAB

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DIPL.-ING. (M.Sc. Eng) Georg Daemisch

Introduction:

The EOL (End of Life) condition of transformers is a very unclear and controversial issue. The data and numerical values found in the literature differ vastly and make it virtually impossible, at the end of the day, to obtain a clear assessment of the situation and ultimately leave the user alone with his or her problems. A closer look at the matter makes it obvious, however, that there can be no such thing as a universal, generally applicable rule. First of all, it is necessary to define what exactly this problem signifies, and to what extent the problem is of a technical or of an economic nature. One thing is certain: the technical conditions of this condition alone are entirely unclear, and all data found in the literature are as much correct as they are incorrect. That is why we shall attempt, in the following, to establish a guideline, which will allow every user to select the most feasible procedure(s) for his or her particular plant. An entirely novel solution to the problem, to be introduced here, will be the so-called PoAB factor (Probability of Advanced Breakdown).

1. What does the literature tell us?

A widely used method of assessment, which clings to furan analysis, postulates that furan values above 5 mg/kg will lead to a value of below 200 DP, effectively ruling out safe and reliable operation in the future. Other authors take an even more stringent position, postulating 300 DP minimum. And there are other authors who claim that transformers with a 200 DP can be operated for many more years without any problems. Practical experience has shown, however, that transformers with a 400 DP (based on the furan value) have a high tendency to fail and that a closer look at such transformers (DP profile) will usually also reveal an EOL status of insulation. This obviously goes to show that any assessments based on the furan values are more of a hindrance than a help. Needless to say that this assessment methodology becomes even more questionable in cases where the materials used in the transformer are unknown. I.e. whether or not thermally stabilized paper was used, for instance. Matters become altogether complicated when trying to assess younger transformer types, which frequently contain a lot less cellulose than their older counterparts. Another issue, which will open up an entirely new avenue of discussion, is whether or not transformers should be generally assessed on the basis of their paper's condition. The troubleshooting procedures required in case of cellulose consumption, i.e. in case of a general deterioration of the DP value, are naturally quite labor and cost-intensive in order to restore correct operating condition through a complete retrofit of the coil windings. In such cases, it is necessary to go beyond the conventional assessments according to which this procedure helps recover approximately 80% of the costs of a newly procured transformer. It is also necessary to take into account a number of additional factors for a technically precise as well as economically correct assessment. These issues will be addressed in detail in the following.

Modus operandi of the other market participants:

The following calculation was found in a laboratory report:

Furfuryl alcohol, ppb	0
2 - Furaldehyde, ppb	124
2 – Acetyl furane, ppb	16
5-methyl-2-furfural, ppb	23
Total Furan, ppb vol	173
Degree of Polymerization	690
Elapsed Life, years	10
% Life Used	10.6
Remaining Life, years	16

The precise citation of DP, lifetime consumption ("life used"), and remaining life gives an amazingly accurate-looking, albeit false, impression of the results. In light of the notorious inaccuracy of such measurements, the mere indication of these values in ppb would appear rather unreasonable, especially in view of the fact that most laboratories use 0.01 ppm (i.e. 100 ppb) as the limit of detectability. It is therefore entirely implausible how a measured value as low as ~ 200 ppb (0.02 ppm) should signify a ~30% loss of the overall polymerization value. Although that approach may be based on the fairly "depressing" Chengdong equation, it is not entirely plausible. Even the number of years specified is virtually nonsense, as the transformer had already been 20 years old at that time. So what is the actual meaning of these supposedly 16 years of remaining life, i.e. the 36 years total? Where do the 10.6 years come from? This is actually the reason why DTC decided to introduce the term "substance". The term makes it possible to clearly identify (a) what is actually available; (b) what has been consumed over which period of time; (c) and how will the consumption of the remaining substance affect load and time.

In the case at hand, DTC made the following calculation:
Even when presuming, from a pessimistic stance, that 1/3 of the substance was already used up over a period of 20 years, a typical linear calculation (typically postulated by some authors) would suggest a remaining lifetime of 2 x 20 years = 40 years total. However, when basing one's calculation on the exponential consumption of substance, the realistic remaining lifetime is actually as low as 15-20 years. And even then only in cases where the load has remained consistently low! Moreover, the transformer also exhibits typical design weaknesses as the DGA data indicate zones exposed to increased temperatures and/or PD. In this case, one of the typical problems of furan analysis becomes evident. In cases where only certain sections of the winding are running at increased temperatures, the volume of furans generated will be relatively low; nonetheless, the winding section this affected will fail prematurely. With due consideration of these facts, such transformers will usually be conceded a remaining life of markedly less than 10 years. And if PD is also found by

the measurements recommended in such a case, reliable transformer operation can be no longer guaranteed.

When looking at the associated DGA and oil data (by the way: the most recent lab assessment in 2015 showed only 0.082 ppm furans), it becomes obvious that the DP issue is of no significance either for that case or for operational reliability. The transformer is suffering from thermal and/or dielectric problems, the oils are obviously under strain, and oxygen consumption is increased. A failure of one of the winding sections is likely, certainly in light of the remaining lifetime prognosticated on the basis of the furan analysis.

Oil Temperature	**°C**	60	45
Hydrogen H_2	**[ppm]**	321	371
Oxygen O_2	**[ppm]**	<1000	3671
Nitrogen N_2	**[ppm]**	66451	82108
Carbon Monoxide CO	**[ppm]**	587	673
Carbon Dioxide CO_2	**[ppm]**	3585	1807
Methane CH_4	**[ppm]**	76	93
Ethane C_2H_6	**[ppm]**	151	56
Ethylene C_2H_4	**[ppm]**	7	5
Acetylene C_2H_2	**[ppm]**	<1	0
Propane C_3H_8	**[ppm]**	202	
Propylene C_3H_6	**[ppm]**	28	
Total Gas Content	**[%]**	<7.48	88784
Breakdown Voltage	**kV**	55	
Dielectric loss factor		0.0258	
Water Content	**[mg/kg]**	21	
Acid Number	**[mgKOH/g]**	0.07	
DBPC	**[%]**		
Interfacial Tension	**[mN/m]**	16	
Total Furans	**[mg/kg]**	0.082	0.173

Any user in need of robust and reliable planning parameters will most certainly be at a loss with the foregoing remaining life calculations. The weakness of these calculations is generally known, which is why attempts have been made to find more stringent assessment parameters, e.g. by using health indices. But even these numerical values do not provide any useful instructions on how best to proceed. The question: What does a user really want or need to know for reasonable reserve and replacement planning?
The answer: everything that any of these methods promise yet fail to deliver: When will the transformer fail and how can I prevent an unplanned shutdown by replacing the transformer shortly before its failure?

2. Probability of Advanced Breakdown = PoAB factor

The solution: "Probability of Advanced Breakdown = PoAB factor". While it is difficult indeed to pinpoint this factor, it is nonetheless based on all known transformer data. Hence, the foregoing example was allotted a PoAB > 50% because the DGA data, the oil data, and also the high oxygen consumption suggest that not even the pessimistic, Chendong-based life expectancy will be achieved. The transformer will most likely fail due to a shorted winding anytime during the next 5-7 years, and even earlier in the presence of PD. A transformer whose identical-design brother had previously failed under similar operating conditions would most certainly also be assigned a high PoAB factor as the probability of its failure under these conditions is very high. A very typical and infamous example is the two in parallel connected GSU installed at a NPP in Northern Germany; in that case, after one of the transformers' failure, the parallel transformer had been attested an overall good condition even though it was identical in design and age and had been exposed to identical operating conditions. In that case, the PoAB was > 90%, which turned out to be true. Not surprisingly, the transformer failed shortly after the plant's recommissioning. In cases such as these, mere probability applies!

3. Experiences

Experience has clearly shown that furan values do not provide a reliable clue for a transformer's condition, even less so for an EOL condition. The experiences made differ vastly, as the examples given below clearly show:

3.1 <1 mg/kg 2 FAL = Parts of the cellulose have become completely disintegrated.
3.2 >12 mg/kg 2 FAL = mechanical strength is fully adequate.
3.3 According to the calculation, approximately 400 DP Profile 800 on the bottom, 0 on top, has a mean value of 400; transformer failure; all identical transformers require retrofitting. (they have virtually reached the EOL condition, but their overall substance justifies a retrofit); PoAB factor of the identical Units > 90

Transformers in technical EOL condition.
The following data justify the classification of an EOL condition:

- High content of 2 FAL > 5 mg/kg
- High oxygen consumption = <<20 000 ppm in open and ~ 0 in closed transformers
  Excessive CO_2 = >>6000 in open and >6000 in closed concluded.
- Breakdown voltage < relation BDV/H_2O (impossible to improve even with permanent bypass filtering)
- Overall condition not viable enough to justify a retrofit (age, P_0 etc.)

Example 1:
Network coupler 200 MVA 220/110 kV openly breathing

After rapid substance deterioration had already been heralded in 2000 by the drop of the O_2 value, the EOL condition was finally reached in 2007. A regeneration performed in 1996 would have stopped the transformer's deterioration.

Inspection date	N_2	O_2	CO_2	CO	H2O	NZ	Ud	Footprint	2 - FAL
	ppm (V/V)	ppm (V/V)	ppm (V/V)	ppm (V/V)	mg/kg	mg KOH/g	kV	10^{-3}N/m	mg/kg
22.11.1991	64000	22500	9280	235					
04.01.1993	66400	26300	5860	271					
05.09.1996	64236	21667	4015	340	19	0.109	65.3		
29.03.1998	58200	21000	7150	352					
15.02.2000	56538	18258	4552	354					
04.07.2003	63422	18404	6301	417	15	0.13	79	15	5.63
29.03.2004	55389	18530	7688	505					
14.11.2007	68173	13793	6843	660	17	0.16	48		8.57
10.12.2007					21	0.16	32		8.52
10.12.2007					26	0.17	34		

Example 2:
Supply transformer for aluminum electrolysis 150 MVA 220/33/6 kV

Oil temperature:	50 °
Water content in oil	20 ppm (KF)
Ud	<30 (according to sample treatment 26-80 kV)
Treatment	Online drainage/filtering in bypass

The dissolved water content is smaller since the oil already showed an increased acid content. The low Ud can be attributed to the presence of fibers. Distinct mechanical weakness of the cellulose, i.e. the EOL condition has been reached!

Sample dated	14.12.99	10.05.00	16.11.00	14.09.01	09.11.01
Sampling point	HK *top*	HK *top*	HK *center*	HK *top*	HK *top*
Total gas	92937	32644	49345	48600	64808
N2 nitrogen	65247	19628	31967	32701	43913
O2 oxygen	17921	9571	14951	14474	18683
CO2 carbon dioxide	8993	3289	2324	1186	1875
CO carbon monoxide	546	67	24	98	124
H2 hydrogen	101	17	11	41	60
CH4 methane	22	3	4	18	27
C2 H2 ethyne acetylene	16	7	6	9	10
C2 H4 ethane ethylene	11	6	7	43	65
C2 H6 ethane ethene	14	7	6	6	9
C3 H6 propene propylene	39	29	27	20	36
C3 H8 propane	27	20	18	4	6
Solution pressure	861	284	457	472	617
Code	012001	000000	000000	000000	000000
Insulating oil examination					
Water content	18	22	14		13
Breakdown voltage	33	41	42		80
Furfurol identification					
Mass fraction w	0.32	0.39	0.47		

Example 3:

GSU transformer 6/110 kV 230 MVA on the right, highlighted in black for comparison purposes.

Distinct EOL condition found. Very distinct differences evident between the individual transformers in the various different stages.

Gas in oil analysis				
Overall gas	72995	102226	88796	102600
N2 Nitrogen	52512	67815	70174	78700
O2 Oxygen	**19647**	**27679**	**7596**	**13300**
CO2 Carbon Dioxide	**666**	**4881**	**7495**	**9300**
CO Carbon Monoxide	153	309	690	900
H2 Hydrogen	**10**	**11**	**129**	**37**
CH4 Methane	4	44	190	11
C2 H2 Ethyne Acetylene	<1	4	1	1
C2 H4 Ethane Ethylene	1	249	142	9
C2 H6 Ethane Ethene	1	40	362	8
C3 H6 Propane Propylene	1	1112	451	300
C3 H8 Propane	<1	82	1566	51
Solution pressure	720	940	852	980
Insulating oil examination				
Water content	**6**	**10**	**37.5**	**29**
Refractive index			1.4817	1.5
Total acid number	**0.01**	**0.03**	**0.21**	**0.18**
Breakdown voltage	**70**	**88**	**39**	**21**
Tan Delta	0.004	0.0076	0.01325	0.06
Furfurol determination				
Mass fraction w	<0,05	0.07	0,26	0.97

The three examples above show a distinct technical EOL condition. An overall assessment is required in this case. BDV plays an important role. Any BDV which cannot be set right to the correct values even by permanent filtering indicates a distinct EOL criterion.

4. Economic EOL

An economic EOL may occur in addition to a technical EOL. An economic EOL may be due to a variety of different reasons. One possible cause are very old transformers whose losses, notably their no-load losses, are very high; another possible cause may be noise development.

Another aspect is risk analysis. Transformers in key asset positions such as e.g. GSU transformers in power plants may get so negative an assessment as to justify their decommissioning simply due to their age and the associated increased risk. Naturally, similar situations are also conceivable for the industrial sector.

5. Modern transformers with reduced cellulose content.

Another new challenge to be faced will be the new, modern-design transformers with their reduced cellulose content. These transformers (typically GSU and electrolysis transformers) have a low-voltage winding made with paperless CTCs and a high-voltage winding made e.g. with thermally stabilized paper. Neither material allows the non-invasive assessment of the insulation condition. It is safe to assume that both the CTCs' insulating varnish and their paper is affected be aging, but there are as yet no known diagnostic instruments to gauge the aging of these materials. Here we have ample room for scientific investigation.

6. Executive summary:

Given an adequate level of professional expertise, it is possible to establish EOL criteria for classic-design transformers equipped with classic materials and to justify these criteria. If the materials used in a transformer are unknown, or if their ageing behavior is unclear, it will be difficult, if not impossible, according to current knowledge, to reach any definite conclusions. Here, we are calling upon science to show new ways for assessing the substance consumption even of those transformers in order to provide the users with the necessary instruments and the end customers with the anticipated security of supply.

Literature.

IEC 60599 guide for interpretation of DGA results

IEC 69422 Mineral insulating oils in electrical equipment supervision and maintenance guidance.

Universal fault triangle in transformer diagnostics. By: Dr. Ekhard Bräsel and Dr. Ute Sasum, 2009

Hermetische Bedingungen für die Gas in Öl Analyse *[Hermetic conditions for gas-in-oil analysis]* by Dr. Ekhard Bräsel and Dr. Ute Sasum, 2012.

New Concepts for Prevention of Ageing by means of On-line Degassing and Drying

and Hermetical Sealing of Power Transformers. Cigre 2004 By S. Tenbohlen et al.

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DTC – Daemisch Transformer Consult
Georg Daemisch
Alte Nürnberger Strasse 32 a
93055 Regensburg
Tel.: +49 (0) 941 87867
E-mail: daemisch@didee.de

Education Profile
M.Sc.(EE), Electrical Power Engineering, Karlsruhe University, Germany

Professional Career

- DTC (Daemisch Transformer Consult) specialized in consulting for transformers and performing online treatment of transformers and life time assessments – 2005 until now
- Owner and managing director of DIDEE GmbH (Daemisch Industriedienstleistungen GmbH) since 1992 until now
- Self-employed – 1991
- Ginsbury Electronic – 1988
- Sales Engineer for Southern Europe for MR (Maschinenfabrik Reinhausen) in Regensburg/Germany for OLTC's – 1985
- Sales Engineer for big power transformers for BBC Mannheim (ABB) for Latin America, the Near East and other areas – 1978
- Sales Engineer for small- and medium-sized transformers for TRAFO UNION (Siemens/AEG) – 1975