Some practical aspects for the life-enhancement of power transformers

by
Josef Altmann, ARS-Altmann Group
www.ars-altmann.com

1. Introduction

The life-expectancy of power transformers and their long-term reliability is mainly determined by the life-expectancy of their hard insulants (Kraft paper, boards etc.)

The reason is obvious – there is always the possibility, without incurring larger problems to replace almost all the aged parts of a transformer (e.g. bushings , oil filling etc.), but not its hard insulants.

The replacement of hard insulants means here de-facto the rewinding of the transformer and corresponding costs are comparable with the purchase price of a new transformer. In most cases any rewinding of transformers becomes too costly and economically unviable.

The user, under given conditions, has basically only two options:

- o do nothing, reduce its maintenance costs on the norm-requested steps only and buy a suitable back-up unit(s) to cover the inevitable breakdown of its transformer(s)
- o find a suitable and relevant diagnostic method for the evaluation of the aging processes, especially for the evaluation of the intensity of the aging of hard insulants of any given transformer(s): and based on the acquired data, find the way to reduce the aging velocity to postpone the replacement of your transformer.

The first approach is unfortunately the most frequent, but the final results are too costly and dangerous. The second, more reasonable and logical approach is not applied, because it represents „costs & effort“. Up until to now there hasn´t been any existing, widely acceptable and practice-orientated methods of how to perform a relevant diagnosis of the specific aging problems of transformers: and subsequently, how to handle the given problems simply and effectively.

2. The basic factors determining the aging intensity of transformers

The degradation of hard insulants of any oil-immersed power transformer is generally determined by folowing factors:

2.1 transformer temperature and loading

2.2 number and extent of its internal faults

2.3 oxygen contamination

2.4 water contamination

2.5 contamination by aging products

ad 2.1) The degradation of cellulose insulants and the loss of their life-expectancy is generally determined by the temperature. The corresponding Arrhenius or Montsinger equation , according to e.g. [L1] is :

(1) $$t = \frac{0.004}{A} e^{\frac{13600}{T+273}}$$

where :

t …. residual life-expectancy of cellulose in hours

T … temperature ^{o}C

A … constant value depending of operational conditions

Most often and most used illustrations of this relation says :

Any (long-term) decrease of a transformer temperature for 6^{o}C [L1, L2], respectively for 7^{o}C [L3], **doubles its life-expectancy**

The relation (1) shows very clearly that the residual life-expectancy of hard insulants and therefore the transformer as the whole, strongly depends on the temperature T and one constant, the A-value.

The using of the formulae (1) for the evaluation od the residual life-expectancy of the specific transformer therefore depends on the quantification of the constant A, which is very difficult or even impossible.

The basic problem is, that A-value doesn´t depend only on operational (boundary) conditions as indicates [L1, L2], but depends on many other factors as DP-value of a paper (initial condition) , contamination degree of a transformer etc.,etc.

The evaluation of the A-value is obviously too complex and any direct reading of the A-value of a transformer is in principle impossible. The relation (1) has for every day practice only a „academic“ value.

From the „practical“ point of view, the relation (1) gives us therefore only one, but very important, piece of information.

This determines very clearly that a relatively small decrease of the transformer temperature induces a strong decrease in the ageing process of the hard insulants, and subsequently prolonging its operational life.

Any practice-oriented life-enhacement of a transformer should therefore be started by the decreasing of its operational temperature. This first step is very simple and easy . The setting of the desired temperature level of the temperature governor of a transformer to 10 – 15^{o}C lower, takes a couple of minutes and that is all that is necessary to potentially prolong the life of the transformer.

The effect of this step has to be quantified by an adequate reading of the aging-relevant value, before and after the temperature change.

ad 2.2) the intensity and size of internal faults is often based on the DGA readings These readings gives us indirect information, because we are not able to read the **direct product of a fault - the flow of the specific gases.** The present DGA readings gives us only the secondary effect of this fault - which is the absolute gas levels in the oil filling of a main tank under so-called equilibruim conditions. Under these present conditions the only real check of the size and relevancy of faults is the disassembly of the transformer and the visual check of faults.

It is well known fact, that any present treatments suppress some manifestation of some specific faults. For example, the degassing of the oil inventory seemingly suppresses the production of H2, as a typical product of partial discharge process in a transformer.

But in general, these kinds of treatments are only dealing with the symptoms not the faults, as we are not able to read to true amount of gases which a specific faults imits.

In other words, we know exactly that a specific fault exists there, because every fault produces a specific gas and the DGA identifies it exactly, but we not able to quantify her true extent in the standard measuring units (m3 s-1, kg s-1).

Consequently, we are unable to quantify the effect of any specific treatment the standard way : by the comparison of the gas production before and after treatment.

Unfortunately, these basic physical facts are very often and completely forgotten - the transformer can never represent the closed system. This means the gases, more or less freely, infiltrate and escape this system. The standard DGA , performed under so-called equilibrium conditions, is simply not able to quantify that kind of gas transportation [L4] and subsequently the true relevance of the faults.

ad 2.3) any higher level of moisture in hard insulants represents not only the factor which strongly accelerates their aging and decreases the long-term reliability of a transformer that way, but strongly and immediately reduces its short-term reliability . The higher moisture level in the oil under higher operational temperatures decreases the dielectric strength of the oil

The standard relation between the aging of the paper and moisture says, that any increase of the water content in paper, accelerates the aging ca 2-times [L1]. For more detailed description of mentioned process, see [L7,8, 17].

Nevertheless, this presumption is not always correct. Some transformers with the water content in paper over 5 – 6% are working for more than 20 years without any bigger problems.

In general, the negative effect of the moisture in paper and boards is well documented, embeded in norms and therefore the wet transformers have to be dried .

For a critical comparison of dehydration methods, see [L5].

Because an exact quantification of the moisture - aging relation is missing: the rule : ***the more dehydration-the better*** is applied.

For heavy water-contaminated transformers, where the Qp-value (averaged water content on paper) is over 3- 4 %), the standard recomendation is only to slowly decrease the Qp-value to ca 2% This is directly due to a lost of clamping forces in the winding [L15] of a transformer and the subsequent loss of its short-circuit strength.

If it is really necessary to decrease the Qp-level from, say from 4% to 1-1.5%, and the dehydration is performed on-line, it is always recomended to open the transformer and to check the real value of clamping forces..

The relevant and sufficiently precise evaluation of the amount of water in the cellulose is very important before and , say one- two month, after the dehydration.

And we face another difficulty again. Present evaluation methods of the amount of water in the cellulose of power transformers are not only imprecise, but can be, in the specific cases, highly misleading.

In the daily practice indirect methods are often used:

- reading of the water content in oil (Qw-value) by Karl-Fisher (KF-method) + reading one temperature of a transformer (T)
- evaluation of the water content in paper (Qp-level) based on the Nielsen or Piper chart

The practice shows that this method, although very simple, has very serious drawbacks:

The KF-method reads, by aged transformers, inadequate high Qw-levels in oil [L6] which subsequently leads to inadequate high Qp-levels in paper.

The same drawbacks show the direct readings of the Qp-level in the paper (RVM , FDS), especially by heavy aged transformers [L1].

The consequences of this incorrect diagnosis are generally very dangerous. The basically „dry“ transformers are evaluated as „wet“, or even very „wet“, and their repeated dehydration harms, or even deteriorates not only their oil fillings but their hard insulants as well [L8].

To minimaze the mentioned drawbacks a new approach consisting of the measuring unit SIMMS [L9] and the software TRACONAL [L10] was developed:

The SIMMS :

- The oil is continously and safely removed from the oil-cellulose insulation system, the integrated capacity sensor reads the relative humidity of the oil which is then forced back into the transformer. The oil cannot therefore be in any way contaminated from the air surroundings.
- the upper and bottom temperature of the oil-cellulose system of the transformer is measured

Subsequently, the SIMMS checks and evalutes the equlibrium of the given transformer. This in-situ method excludes most of above mentioned measuring errors and gives us desired data for their subsequent processing by the TRACONAL.

The TRACONAL then enables not only the evaluation of the Qp-level, but other important information about the transformer e.g. what amount of the water is necessary to remove for its insulation system to achieve the requested minimal dielectric strenght (Ud-value), what temperature may not be exceeded to keep the max. allowed water content in the oil etc. For detailed explanations all potentials of the TRACONAL, see [L10].

The absolutely new and extremely important feature of the TRACONAL is the cross-checking of evaluated & measured values : this means the **quick and relevant verification of the evaluated Qp-value by the independently measured value of the dielectric strength of the oil** [L7,10].

ad 2.4) the oxygen in the oil filling represents always the mean contaminant which dominantly affects the intensity of oxidation ageing of the oil filling and hard insulants of any oil-immersed transformer.

The ideal solution to minimize this, generally very negative effect of the O2-infiltration into a transformer, is of course effective hermetization. This method is especially advantageous for the heavy loaded transformers, working at high operational temperatures and by the high air humidity.

The effective hermetization can substantially increase the potential life-expectancy of any transformer. The well hermetized transformer, with O2-level in the oil under 300ppm, has ca 50-times lower velocity of ageing than the transformer which oil filling is fully saturated with the O2 [L11].

Even O2-level about 2000 – 4000 ppm, which corresponds to a standard hermetization level, already decreases the mentioned velocity of ageing, by at least twice.

In this case, the proper solution is quite simple. All rapid ageing transformers should be properly hermetized as soon as possible. If a standard hermetization is not available or too costly (bag-in-tank), the O2-level in the oil has to be reduced another way e.g. by on-line degasing.

But, it is very important, that only the removal of O2, H2O + products of ageing, (undesired substances,) from the oil is allowed here. The high vacuum and high temperature procesess are strictly forbidden, to avoid the removal of light fractions from the oil and the subsequent degradation of oil and cellulose.

The critical comparison of existing hermetization methods gives e.g.[L12].

ad 2.5) ageing products represents another negative factor which always boosts the ageing process of the insulation system of any transformer.

The ageing process in hard insulants is always strongly affected by the synergetic effect of the water, oxygen, ageing products in the oil, and the temperature of the insulation system [L2].

The dangers of long-term deterioration of insulation systems by typical ageing products such as organic acids, ketones, metallic soaps and aldehyds is well-known. Moreover, the proper evaluation of the danger is simply and precise - by the NN-number. Unfortunately, most of users are unable to do the proper steps to avoid the worst.

The rules and adequate treatments of an affected transformer are simple and effective:

If NN > 0.1 mg KOH / g oil, the replacement or reclaiming of oil filling is absolutely necessary.

3. Economic aspects of life-enhacement of transformers

The maintenance of a power transformer has to be always correctly economically analyzed to give us the clear picture of what to do with a specific transformer and what not.

The basic criteria of any life-enhacement is the calculation of the savings induced by the prolongation of the replacement of any old transformer.

The analysis is based on the simple comparison of two variants:

- minimum benefit of prolonged replacement = the defered interest on the expenditure consisting of the purchase price of a new transformer + all costs which will be reqiured to replace the old one.
- maximum benefit based on lower losses of a brand new transformer

This analysis represents a multi-parameter problem which can be very difficult to solve.

The freeware SINDRET[L13] can help here, especially in the evaluation of all potential alternatives and the combinations of the costs of life-enhacement methods, versus the prolonged life-time of the specific transformer.

For more detailed and relevant insight, the plausible determination of the “instant” state of the transformer is needed and of course the relevant estimations of the costs of its life-enhacement.

And there are further problems :

- we are not able to determine the (instantaneous) degree of aging of hard insulants without partial disassembly of the transformer
- the real quantification of the effect of a life-enhacement is very difficult

For a first and basic economic assesssment of the replace / non-replace problem is based on a very simply relation – are maximal attainable savings induced by postponed replacement of the old transformer comparable with the purchase price of the new one ? .

The first estimation is therefore performed without any costs. In the second step are the real costs are calculated and in succesive steps all relevant alternatives are evaluated.

The practical examples of SINDRET calculations are shown in [L14].

4. The new methods of evaluating the aging rate of hard insulants.

Under present conditions only one objective method exists to check the degree of aging of hard insulants: To open the transformer, to take samples of paper from the most stressed parts, and to directly check the mechanical strength of the samples.

This method is the most objective, but there are some drawbacks as well:

- we don´t know exactly where the most damaged hard insulants are
- this method is too time-consuming and unsuitable for operational conditions

All other standard methods are unsuitable, e.g. furan analysis [L3], because they are simply not able to read the aging rate of hard insulants directly, quickly and precisely enough.

The most promising is the on-line DGA (Diluted Gas Analysis). This method is a-priori precise reading of the O2-level (consumed by oxidation aging) and the CO- and CO2-levels as products of the oxidation aging in the given transformer.

Moreover, the measurable dynamic response of the examined system (represented there by the volume of the oil filling of the main tank) is approx. in days- not in months or even years as by furan analysis or NN-readings.

In other words, we are not able to determine the total degree of the aging of hard insulants precisely , but we are able to determine **the rate of their aging in situ, precisely and very quickly**.

The suitable „dynamic" application of the standard on-line DGA enables us to evaluate flows of O2, CO a CO2 and get direct information about the „instantaneous" intensity of the oxidation ageing process in a transformer

This new approach effectively removes the basic disadvantage of the present on-line DGA which works only with absolute levels of mentioned gases in the transformer under quasi-equilibrium (or stationary) conditions. This method cannot be **selective enough, because is not able to read the real flows of gases between the insulation system of the transformer and its surrounding** [L4].

Two new "dynamic" on-line DGA methods are available:

- **QDGA (Q**uantitative **D**iluted **G**as **A**nalysis) uses the known volume of the oil filling of the main tank of a transformer as the measuring capacity and the N2-content in the oil as its so-called calibration gas. By means of purposeful change (degassing) of the oil in the main tank and by the reading of the N2-content in the main tank and in the conservator, it then calculates the throughflow between both tanks. Subsequently , when we simulateneously read the contents of all relevant gases in the both tanks, and we already know the oil throughflow between them, the flow of gases between them can be easily calculated [L4]..
- **GDGA** (**G**radient **D**iluted **G**as **A**nalysis) uses again the known volume of the oil in the main tank as a measuring capacity, but the purposeful change, the degassing of the oil filling of the main tank, is now used in a different way, for the acquirement of so-called saturation curves for all relevant gases. The gradients of all above the mentioned curves are then evaluted in the time-point $t \rightarrow 0$.. The flow of the specific gas is then equal to this gradient – for more details, see [L16].

Both methods are of course not only suitable for the flow quantification of the O2, CO and CO2, but for quantification of flows of all, DGA- measurable, gases in a transformer.

5. Conclusion and Recommendations

The ageing degree of many power transformers is already very serious and their short- and long-term reliability is inevitable low and sinking. Moreover, the trend of degradation is, due to the "avalanche effect" , faster and faster.

It is clear, that there simple isn´t enough money to replace all of them in a reasonable time-period to avoid their incidental failures.

Prolonging their life-expectancy therefore represents an effective method of how to keep them in reliable operation.

At the same time their proper life-enhacement means substantial savings and moreover give us time for the succesive replacement of risky units.

A life-enhacement program is a process which has to start immediately.

The first step of the life-enhacement of a transformer is achievable without any substantial costs. The decreasing of operational temperature of all transformers equipped with a standard temperature control always reduces the aging.

According to the fact, that the standard set point value of most temperature governors is mostly about 60°C and the average air temperature (in Europe) never substantially exceeds 20°C, the new set point value can be set at 40 – 50°C.

Already this a very simple and absolutely "safe" intervention in operation conditions of transformes, this has to reduce the aging rate of their hard insulants by at least half,.

The second step is so-called "categorization". All transformers, older then 10 years, are divided in three groups (A,B,C) according to the value of " Grade-of- Ageing" or GoA-factor :

(2) GoA = A . NN . Qp

where :

A	....	age of transformer (years)
NN	....	Neutralization Number (mg KOH/g oil)
Qp	....	averaged water content in the cellulose (%)

The GoA-factor is the product of three good-measurable quantities (with well-defined mutual synergetical effect) , and the introduction of the GoA- factor makes technical sense. A similar factor was introduced for ageing of transformer oils by Mayers [L18].

Group Quantification according the GoA-factor

GoA	**Group**	**Transformer condition + Recommendation**
0 - 5	A	Good condition, low ageing , no maintenance action necessary
5 - 10	B	Middle contamination, middle ageing, lowered short- and long-term reliabity, dehydration or degasing recommended, hermetization?
10 and more	C	Heavy contamination, strong ageing, very low short- and long-term reliability, immidiate action necessary : reclaiming + on-line dehydration + degasing

Example of Categorization Table

S/N	**A (years)**	**NN (mgKOH/g oil)**	**Qp (%)**	**GoA**	**Group**	**Conclusion & Recommendations**
001	10	0.08	1.4	**1.12**	A	satisfactory. No action necessary
002	25	0.1	3	**7.5**	B	Wet transformer , dehydration necessary Reclaiming necessary in ca 2 years Hermetization?

003	20	0.3	3	**18**	C	Wet transformer, dehydration necessary strong contamination by aging product, oil reclamation necessary asap Hermetization asap

Attention ! For oils with the NN-value over 0.05, SIMMS + TRACONAL should always be used to avoid the systematic error of the KF-reading in aged oils.

The Categorization Table represents the basic info about the instant state of transformers and recommends maintenance actions which improves their instantaneous status and reliability.

The third step - based on the SINDRET calculations, finding the most costs-effective solution for the specific transformer.

The fourth step - the effect of the selected maintenance method has to be always confirmed by using of the standard diagnostic approach - one reading (on-line QDGA or GDGA) before, and after the application.

References:

L1 Saha

Review of Modern Diagnostic Techniques for Assessing Insulation Condition of Aged Transformers
IEEE Transactions on Dielectrics and Electrical Insulation, Vol.10, No.5, October 2003

L2 Sokolov

Impact of Oil Properties and Characteristics on Transformer Reliability
Fifth AVO New Zeeland International Technical Conference, 2006

L3 Hoehlein

Furane als Indikator des Feststoffisolationszustands in Transformatoren – Moeglichkeiten und Grenzen
EW 105,(2006) , Heft 25

L4 Altmann
Quantitative Measurement of Production and Consumption of Gases in Power Transformers

US Patent No.:7.474.186 B2, resp. www.ars-altmann.com /News

L5 Altmann

Maintenance of wet power transformers, Comparison of standard methods and Altmann´s method
www.ars-altmann.com / News / Reports

L6 Sokolov

Transfomer Condicion-based Ranking
Fifth AVO New Zeeland International Technical Conference, 2006

L7 Altmann

Systematishe Fehler bei der Diagnose „feuchter“ Transformatoren
EW 106 (2007) , Heft 7

L8 Altmann

Wasser in gealterten Transformatoren
EW6/2007 resp. www.ars-altmann.com / News / Articles

The water problem of aged transformers
www.ars-altmann.com / News / Papers

L9 Altmann

SIMMS
www.ars-altmann.com / Product Range / SIMMS

L10 Altmann

TRACONAL
www.ars-altmann.com / Product Range / TRACONAL

L11 Lampe, Spicar

Influence of different stress factors on the dielectric and mechanical strength of oil cellulose insulation
CIGRE 1978 Session, August 30

L12 Altmann

Comparison of hermetization methods of power transformers

www.ars-altmann.com / News / Reports

L13 Altmann

SINDRET
www.ars-altmann.com / Goals of Transformer Maintenance / Saving calculator

L14 Altmann

Zum einigen Aspekten eines herausgezoegerten Austauschs eines Leistungstransformators.
EW 6/2006 resp. www.ars-altmann.com / News / Articles

L15 Krause, Goetz

The Change of the Clamping Pressure in Transformer Windings Due to Variation of the Moisture Content.
CIGRE SC12, 1999 Budapest Colloquium

L16 Altmann

Einfluss der Vakuumaufbereitung von Oelen auf Ergebnisse der Gas-in Oel-analyse.
EW 101 (2002),Heft 5

L17 Altmann

The dielectric strength of the transformer oil and its impact on the diagnostic of power transformer
www.ars-altmann.com / News /Articles

L18 Yers, Kelly, Parish

A Guide to Transformer Maintenance
TMI 1981, ISBN 0-039320-00-2