GERIATRICS OF TRANSFORMERS

By

Georg Daemisch

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DIDEE DAEMISCH **I**N**D**USTRI**E**DI**E**NSTLEISTUNGEN

Abstract

"During the 60s and 70s of the previous century, when the majority of the transformers was installed, they were intended to last for a life span of about 30 years. In the meantime, and due to a change in overall conditions brought about by liberalization combined with a variety of political and economic reasons, users have become keenly interested not only in keeping these transformers in service for an indefinite length of time, but in exploiting them up to maximum loading or - even worse – overloading them, something which usually wasn't done at all, particularly for transformers in network applications. The question now is to figure out how to afford the prolonged and higher demand on transformers. The classic tools and test procedures normally at the hands of the transformer user are all based on the behavior of new transformers. Applying these tools to transformers with oil-cellulose insulation systems which have been in use for more than 30 years creates more questions than can be answered at the moment. It is quite common that moisture content, dielectric strength, DGA and other key data will show inconsistent results. These results make it impossible to get a clear picture in order to decide whether a particular transformer can be kept in service, to what degree it can be loaded or even overloaded, or what action is necessary to improve the operational safety level in order to cope with the required load pattern. For this reason, the new "science" - Geriatrics of Transformers – is, at present, not capable of providing immediate satisfactory answers since a number of additional questions must be dealt with regarding additional new tools, data sampling, diagnosing and the establishing of suitable solutions prior to final approval. This paper is aimed primarily at presenting the new questions arising from the practice of evaluation and treating aged transformers, in order to promote discussions and draw the attention of transformer experts to this issue which will be one of the most important innovations in the world of transformers".

Introduction

When ARS-Altmann first began to develop active online transformer processing systems and introduce them for field application some 10 years ago, it first seemed that the problems were limited to dealing with the water contamination of the oil-cellulose systems. The other important issue was to keep the system clear of atmospheric gases. The problem with water, although quite well-known in theory, was an issue then and has still not come to the full attention of all users.

To this day, improperly obtained and documented oil samples continue to instill a false sense of security in most users. Compliance with the original intention implying that the life span of most transformers has usually run its course after 30 years of use and that transformers should be replaced after that point will definitely allow the user to retain the customary diagnostic tools and maintenance philosophies employed and valid so far. The entire diagnostic instruments commonly and widely used right now are based on this concept. With the exception of special transformers used for rectifier operation or in furnace applications, and provided that the transformer is free from design or production errors, it is generally accepted that reliable transformer operation is safely guaranteed for a period of approx. 25 to 30 years without need for special measures. During that period, it is solely the external influences such as overvoltages during thunderstorms, switching manipulations etc. or short-circuits within the power system which may cause internal damages that are easy to detect with the customary diagnostic procedures such as DGA or other well known diagnostic tools. This applies even to generator transformers which - in contrast to power system transformers - are usually operated at nominal load if system temperatures can be kept sufficiently low through adequate cooling.

The so-called Bathtub Curve is used for estimating the frequency of the failure incidents likely to be expected.

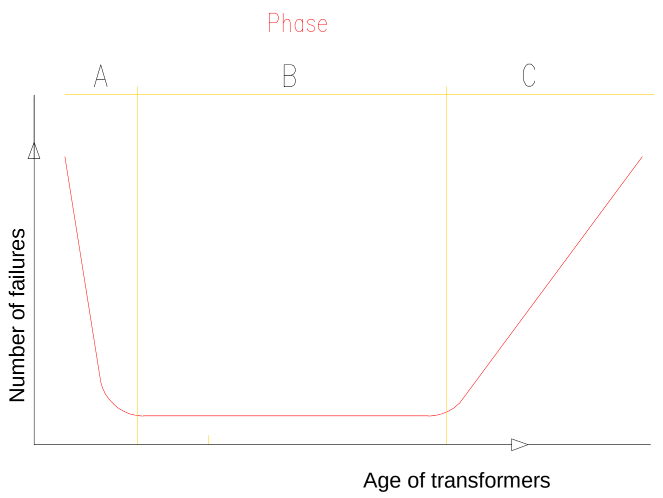

Figure 1
Transformer Failure Rate “Bathtub Curve”

Phase A – new transformers: approx. 1-3 years after commissioning, the number of failures will drop to a very few incidents per annum, even to Zero incidents; any failures occurring during that period are caused mostly by production or design errors (e.g. small leaks, incorrect sensor settings etc.)
Phase B – normal operation: depending on the type, loading and maintenance of contemporary transformers, this phase, where no major failures are likely to occur, may last between 20 and 30 years.

Phase C – rise in the number of incidents: problems mainly caused by ageing.

These types of transformers represent the major part of the population, which is why we give them our special attention. For most of these transformers, we have nonetheless arrived at the end of Phase B or even at phase C of the Bathtub curve where failures are likely to arise with increasing frequency since these transformers have already exceeded their life spans.
It is worth mentioning that modern transformers which are subject to a considerable increase in material exploitation and temperature stress will most certainly no longer comply with the parameters of Bathtub curve shown herein (Phase B is likely to be much shorter in this case), and that they will most likely require greater monitoring intensity since modern transformers are very unlikely to feature the service life reserves noted in older transformers.

As evident from Fig. 1, a user's objective should be to remain in Phase B for as long as possible, and even to return from Phase C to Phase B to the greatest extent possible, through implementation of well-aimed maintenance measures. That way it is possible to achieve an increase in service life reserves of up to 10 years or more for the current transformer population, albeit not without suitable life-prolonging or at least monitoring measures.

Diagnostic procedures

Classic diagnostic procedures such as gas-in-oil analyses, the evaluation of oil data such as dielectric strength, acidity, tan delta, water content according to Karl Fischer (KF), or even more current methods such as the Furan analysis will yield only relative data which - if out of context - do not permit a proper analysis of a transformer's actual condition. On the contrary: more often than not, these data are even contradictory and may leave the field user in a state of considerable confusion. But it is first and foremost the field users and decision-makers which are in the most desperate need of getting proper information on how to proceed in individual cases and how to achieve their preeminent goal – i.e. to ensure a reliable power supply while minimizing investment costs – regardless of and beyond any theoretical deliberations on that subject. The field user needs reliable answers: should he scrap a certain transformer, or keep it in service for an additional limited period of time through implementation of specific measures, or is the transformer likely to continue performing its tasks without limitations for quite some time to come? What is so important to bear in mind is that each transformer is an individual and therefore requires specific and individual consideration. We feel that although some experience and guidance values have been gained so far, we are still far from being able to issue general statements that are safely and wholly applicable to each case.

Experiences

When ARS Altmann first began implementing their online treatment systems for aged transformers, the scope of problems was limited mostly to moisture saturation of the cellulose and the removal of the water thus retained. Today, nearly everyone has come around to realize that this is an important concern, although it would appear that quite a number of users still fail to comprehend the full importance of this issue. Also, conventional evaluation of the data gained from oil samples remains limited to an assessment of the oil data per se, without due consideration of the overall oil-cellulose system. Consequently, conventional evaluation usually deals only with whether the oil of a sample usually taken under random conditions complies with the admissible values or not. If no reference is made to the temperature at the time of sampling, a water content of e.g. 20ppm may be either perfectly uncritical (by normal full power temperature – say over 50C) or dangerously alarming (by cold transformer – say below 20C). What is even more complex is the issue of dielectric strength. Conventional thinking more often than not equates a low dielectric strength to water contamination. At a closer look, however, it becomes increasingly obvious that this issue involves a whole cluster of complex and associated concerns requiring a comprehensive and conclusive view of the various measuring values and the oil-cellulose system in conjunction with the systematic feedback effects. Since introducing remote monitoring of the ARS systems, it has been documented with ever-increasing clarity that in an actual field situation, water content according to KF, dielectric strength, and water separation will often behave vastly different from any theoretical notions initially entertained. For ARS equipment, the volumetric representation of the separated water leaves no room for misinterpretation. If the expected amount of water in the cellulose as determined on the basis of the water content in oil according to KF and on the basis of the water content (Cp) determined by Nielsen/Piper diagrams is not actually present even though all other parameters were properly in place, the problem is most likely due to a systemic error which can at that point no longer be explained away by incorrect sampling or other improbabilities.

Three typical cases:

1. Medium or low water content Cw as per KF: the dielectric strength is considerably below the standard profile for Ud = Ud (Cw); see Fig. 2 – water separation corresponds to measurement as per KF.

2. Water content as per KF and dielectric strength correspond to the profile; water separation corresponds to measurement as per KF.

3. Water content as per KF is relatively high, the dielectric strength is considerably above the standard profile; water separation is considerably below the measurement as per KF.

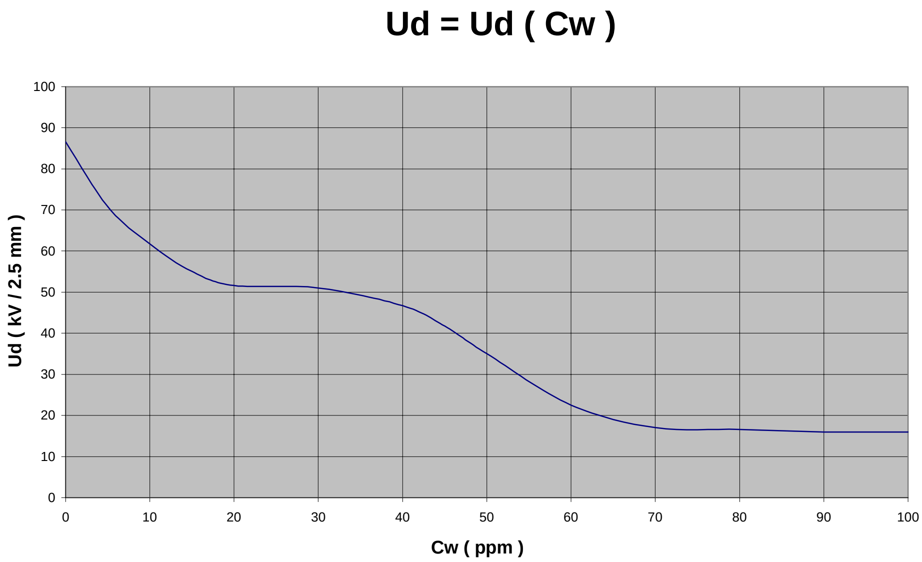

Figure 2
Disruptive Strength of the Oil as a Function of the Water Content in the Oil (as per VDEW Ölbuch [‘Oil Book’] Volume 2)

If, in the latter case, a parallel measuring of the water content of aged oil is performed both by KF and with a probe (e.g. Vaisala), the water content values displayed for KF are usually very different from the values displayed for the probe, i.e. the KF results are usually considerably higher. When these measurements are done with new oil, however, KF and measuring values achieved via probe are basically equal. What matters, however, is that the KF-Cw values are often incongruent with the water separation (ml/24 h) and the dielectric strength Ud (kV/2.5mm), although for measurements with Vaisala, the broad tendency of Cw data is basically congruent with Ud and water separation is by all means considerably better, even for extremely aged oil (provided the oil’s particle content is low or tends towards Zero!).
In these cases, the neutralization figure is nearly always above 0.1 and the oil present is usually non-inhibited and very aged and appears so to the naked eye.

A single glance at this confusing situation automatically leads to a number of new questions: What am I really measuring with KF? How can I achieve a well-aimed diagnosis and evaluation of the complex oil-cellulose system? Which problems are only oil-related? Which problems are only cellulose-related? What is the data’s significance for the transformer’s condition? What are the general conditions that must be present in order to guarantee the operational safety and longevity of the transformer in question? How do I achieve these conditions and which measuring values do I need to document them? Which measures have to be performed to the transformer to achieve that end? How to relate for instance the water content and Ud with the results gained from other analyses such as gas-in-oil or the Furan analysis?

The status of the currently ongoing discussions on these issues indicates beyond a doubt the enormous need for clarification. To this date it would seem as if the various different data bear no relationship with one another, or that they even contradict each other. For instance, one of the more recent Cigre papers (Draft Final Report 1218 Rev2) comes to the conclusion that KF undervalues the water content. This may well be the case if the oil is the sole factor taken into account. It is our experience, however, that in the presence of extremely aged oil the water content of the entire transformer (water in cellulose + water in oil) is more likely to be overvalued.
According to our own observations, however, the old tenet saying that more than 90% of the water is retained in the cellulose has lost none of its validity. Even the basic validity of the relation Cp = Cp (Cw, T) according to the Nielsen profiles is supported by our experiences. Using the daily values of the ARS-VS systems as a basis, it is possible to estimate even those water contents in oil which, although congruent with the measurements by probe, are in certain cases contradictory to the values determined per KF, as evident from the following table. Here, the Cp values were determined using either the Cw values as per KF, or the separation rate, or – wherever possible - by probe measurement.

Table 1
Water Content in Oil Cw Measured/Calculated by KF, VS, Probe against D.S.

Transformer	**Acidity** (mg KOH/g)	**Cw KF** (ppm)	**Cw VS** calculated(ppm)	**Cw probe** (ppm)	**D.S.** (kV/2.5mm)
150MVA start of treatment	0.1	18	~10-15		26-83
150MVA end of treatment	0.1	15	~ 10		50
20MVA	0.01	45	~40		28
16MVA distrb. Tr.	~0.2	32	~10	8	60
90MVA	~0.2	32-36	~20	-	75-83
600MVA	0.16	27	~20	15	<80
16MVA Gen.Tr.	0.2	54	~20	12	<80

This table is a clear representation of the cases outlined above. In the case of the 150MVA transformers, the cellulose disintegration had progressed to such an extent that the excessive accretion of fibres present caused the dielectric strength to fall way below the value normally expected for the water content present.

Moreover, the accretion of fibres was more or less stochastic and the fibres may even have accumulated in clusters since dielectric strength values ranging between 26 and 83 KV were measured for a sampling evaluation of various different batches by different laboratories. During the course of the treatment, the depth filter integrated in the water extractor (Altmann VS-06) lead to a marked improvement in overall conditions. It was clear, however, that regardless of the measures employed, this transformer could no longer be kept alive for any considerable length of time. The combination of water extraction, reduction of the atmospheric gases and deep filtering nonetheless permitted a secure phase-out operation until delivery of the replacement transformer.

The 20MVA transformer showed perfectly congruent behavior, even the water separation met everyone's expectations. After removal of 14 liters of water and reduction of the Cp value by nearly 5% to less than 2.5%, the dielectric strength rose to values in excess of 80kV/2.5mm which are generally expected for the temperatures commonly present during operation; the transformer will in the foreseeable future be fully operational without limitations.

The last three cases are not as unambiguous, and the figures are contradictory. Despite the presence of a high or even very high water content as per KF, the dielectric strength measured is way above the values which should be expected. In all three cases, measurement by probe and/or evaluation of the water separation indicates a much lower water content than should be expected according to KF. In all three cases the neutralization number is markedly above 0.1 mgKOH/g. Since the only constant value is ultimately the water content of the cellulose (Cp), the following table shows how different the results achieved can be.

Table 2
Water Content in Cellulose Cp Measured/Calculated by KF, VS, Probe with Reference to Acidity

Transformer	**Acidity** (mg KOH/g)	**Cp KF** [%]	**Cp VS calculated** [%]	**Cp probe** [%]	**Cp VS/KF**
150MVA start of treatm.	0.1	3.5	~ 2.5	-	70/100
20MVA	0.01	4.5	~4.5	-	100/100
16MVA distrb. Tr.	appr.0.2	4.5	~2	2	45/100
90MVA	appr.0.2	3.5-4%	~2.5-2.8	-	70/100
600MVA	0.16	3.5	~2.5	2.3	71/100
16MVA Gen.Tr.	0.2	>5	~2.5	2.5	50/100

The above table shows that the evaluation of the water content according to KF for Cp determination will usually lead to misinterpretations whenever a high acid content indicates the presence of excessively aged oil. On the other hand, the Cp value is essentially the only true and absolute moisture indicator of the cellulose (if other sources of contamination such as atmospheric humidity or cooling water can be excluded, the Cp value can also serve as an excellent ageing indicator). But the question remains how to obtain this value with any measure of certainty, since in addition to the systematic deviations mentioned above, the reliability of classic sampling is just as critical, not only due to the inevitable tolerances, but also due to the temperatures profile in the transformer which are difficult to fathom, especially for ON cooled transformers. A series of measurements conducted just recently has shown that the temperature conditions inside transformers are often much more complex than generally assumed. For this reason RVM measuring has once again increased in significance. Without a doubt, this system features certain advantages, but this method is as off-line measuring costly and comes with certain systematic problems for cold measuring. Improving the classic warm measuring method for on-line measuring of the water content Cw while maintaining reliable and simultaneous measuring of the top and bottom temperatures in the circulating oil area would suggest that adequately reliable data can be obtained with this method while keeping costs at an acceptable level.

Questions

Although dealing with each single problem arising from the field application of transformer processing would obviously go beyond the scope of this context, there are nonetheless a number of core issues which deserve special attention in our efforts to keep up the reliable operation of transformers whose intended life span has already run out for an extended period of time, possibly even under aggravated conditions, while at all times taking into account the issue of economic feasibility.

Although everyone will surely agree that the water content of the cellulose has to be kept low, this issue immediately leads to the question as to which level can be considered adequate, optimal, or compulsory. Obviously, the discussions on that issue have only just begun and right now, Cp values in the ranges of <2.5%, 2% or even 1.5% are being discussed as target values (the core issue of this discussion and the most important topic requiring clarification before any measures are implemented are the marginal prerequisites which have to be taken into account or put in place).

The interplay between aged oil and cellulose data would also appear to require additional in-depth examination since the statements contained in the current literature are more often than not contradictory, and some issues appear obviously incongruent with the field experiences gained by us.

Therefore the question should be raised what to do or whether to do anything at all in cases where the dielectrics seem adequate enough, but where other indicators such as oxygen consumption and other gas data in the oil would seem to indicate potentially critical processes.

A fresh approach to the issues of inhibition and re-inhibition would seem equally advantageous, especially in connection with oil regeneration, in an effort to find the most economic method for recovering a stable oil free from ageing byproducts. A fresh approach to the limit values of the acid content should at least be considered. It is certainly correct that a transformer intended to be taken out of service after 30 years of use will hardly require any measures in that respect since the oil content will – bar some special exceptions – most likely remain adequately stable during that period of time. If operation is intended to be continued beyond that time, however, the modus operandi will also require a fresh approach.

Another question worth raising is the need for economically feasible air insulation systems to reduce the penetration of atmospheric oxygen and thus to ensure the stabilization of a processed system.

Summary and outlook

In the context of this paper, we have made a conscious effort to avoid presenting ready-made recipes or data deemed by us as conclusive, even though we have accumulated a certain wealth of ideas and findings which we would like to incorporate in the discussion. The above notwithstanding, the issue of how to deal with the overaged transformer population is still in its beginning stages and it would appear that a number of the concerns involved still require clarification from a scientific point of view as well. The first and foremost purpose of this paper is to draw attention to the core issue of this problem, and to present some indications gained from our field experience as to the direction the further developments should take. Also, equipment and methods promising to solve likely problems were not very well thought-out and were put on the market in recent times. The verifiability of the actual success of certain measures deserves investigation as well. Also, some thought should be spared on what can still be expected of a considerably aged system and which measures might be of a mere cosmetic nature or might even be dangerous and therefore counterproductive. It will be necessary to develop scientifically supported models for determining which data can still be feasibly expected from an aged system, and how to realize these models in the gentlest and most cost-conscious manner.

It would also appear that a distinction needs to be made between transformers working at high temperatures and transformers operating under relatively cold conditions. It is especially the latter which are the most puzzling to evaluate since on the one hand the electrical data are OK and no further interventions seem required, while on the other hand indications e.g. from gas analyses would portend that action must be taken after all, although the type of action required is not always clear.

Our field experience has taught us time and again that there are no generally valid answers: a general answer e.g. as to which water content should be set for aged cellulose is simply not possible since the countless different marginal conditions will naturally lead to innumerable different answers. And let’s not forget that each transformer is an individual as soon as it leaves the factory, with individual characteristics that become ever more evident with increasing age.

All things being equal, we see no reason to keep entirely quiet about the fact that due to our field experience gained and developments, we feel quite capable of presenting sensible diagnoses and proposing economically feasible suggestions. Each procedure must always start with the collection of reliable data which, following a field-oriented interpretation, will point the way to appropriate measures whose economic efficiency will allow a wide-ranging application. Users of large power transformers (above 100MVA) may, in view of the high investment costs for replacements, be more willing to decide in favor of cost-intensive measures, but should bear in mind that the majority of the transformers concerned has a nominal power of less than 100MVA which is why the investment costs for continued operation have to be kept within a tight range.

Still, solutions have to be found which will cover the following issues:

- Oil condition (acidity, sludge, particles, gas content)
- Conservator systems (penetration of atmospheric gases)
- Cellulose condition (water/sludge)

If we manage to get a grip on these areas, both from a diagnostic and treatment-related point of view, we will be able to supply the user with economically feasible yet reliable methods which, in spite of liberalization and cuts in investment and maintenance budgets, will guarantee a safe and reliable energy supply even with the „old dogs“ from the past millennium, and leave behind any scary visions of “Californian conditions” as a flimsy spectre of no consequence.

*M.Sc.(Eng.) Georg Daemisch
Owner and managing director of DIDEE (Daemisch Industriedienstleistungen) specialized in consulting for transformers and in close partnership with ARS-Altmann for nearly ten years, the leading company for On-Line treatment of transformers.
Sales Engineer for OLTC's in southern Europe for MR (Maschinenfabrik Reinhausen) in Regensburg/Germany
Sales Engineer for large power transformers for BBC Mannheim (ABB) in Latin America, Near East and other areas.
Sales Engineer for small and middle sized transformers for TRAFO UNION (Siemens/AEG)
Studies carried out in Karlsruhe, Germany, up to Dipl. Ing. (electrical power engineering) level.