Beneficial investment for transformer maintenance

> The main reasons for transformer failure are exploitation conditions and external factors

ABSTRACT

Transformer is the most important and pricey piece of equipment in the transmission system, so an adequate maintenance strategy is required to ensure uninterrupted electricity supply, preserve transformer life and minimize the investment. The crucial phases to ensure reliable and economical exploitation of a transformer within any maintenance strategy are inspection and audit of the manufacturing process, and adequate preparation before it is energized. Dissolved gas analysis (DGA) applied periodically is the most cost-effective test for transformers. However, excessive maintenance, tests or treatment can cause more damage to the insulating materials than prevent the potential failure. A specific maintenance policy is driven by economic aspects, consequences of power outage, insurance companies, and the knowledge and beliefs of the transformer owner. Despite proper maintenance, a small percentage of transformers will inevitably fail.

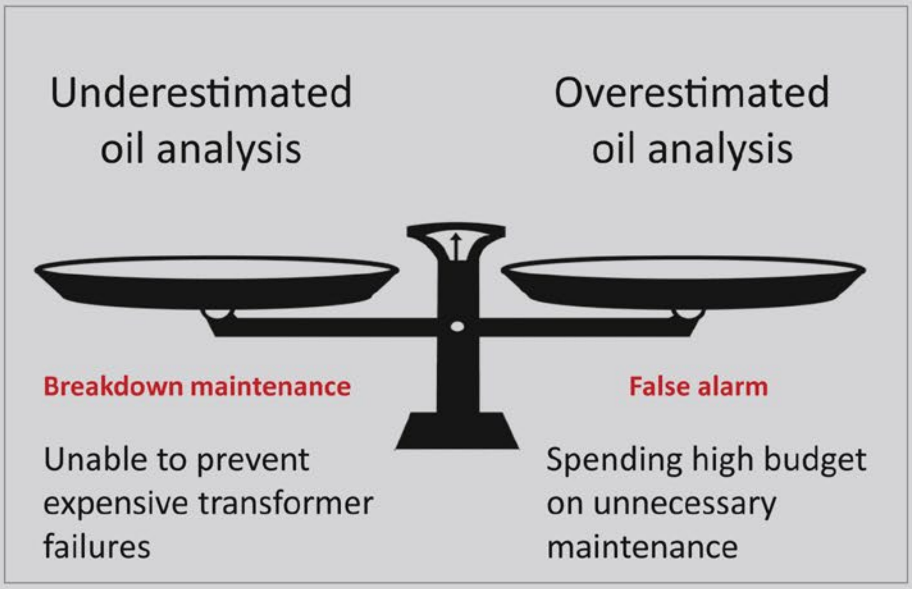

Figure 1. The right balance for benefiting from transformer oil analysis

1. Introduction

Transformers and oil-filled equipment are one of the most important and vital rings in the electricity supply chain, allowing efficient and inexpensive transport of energy. The transformer technology is about 120 years old and has not changed much since the 19th century. The transformers have remained reliable and mostly free of special or sophisticated maintenance for all these years, although the power and voltage increase and ratio of MVA to insulation weight decrease significantly. Most of manufacturers and planners create sophisticated, quality products tailored to very tight specifications. However, although transformer failures are rare, when they happen, they are often quite spectacular. Besides the bad publicity when such a failure occurs, it is also not easy to find a spare unit for this most important and pricey piece of equipment in the transmission system.

It is often a case that the transformer owner has to select the most adequate strategy to ensure uninterrupted electricity supply, to preserve transformer life and, at same time, to invest as less as possible. Sometimes the cost of the tests and maintenance can be higher than the price of the equipment itself.

Any misunderstanding or compromises in the maintenance policy will lead to either unrevealed failure or unnecessary and expensive maintenance. The advantages of each maintenance philosophy will be explained from the user point of view.

Most transformers do not fail because of the degradation process of oil and/or paper, not even in the presence of moderate content of moisture. The main reasons for transformer failure are exploitation conditions and external conditions. Even the most well-constructed and well-maintained transformer will fail in extreme loading condition or due to external incidents. Correspondingly, even a transformer with a very aged insulation and extreme humidity can be energized for long periods. The main puzzle for many engineers and experts in this field around the world is defining the right investment needed to optimize the exploitation of the transformer and finding the right moment for replacement. Abandoning a unit that is still healthy is very expensive and undesirable as new transformers may sometimes impose more challenges than transformers of old designs.

The life of transformer or any other electrical equipment using organic materials for insulation and/or mechanical construction is variable and dependent on many controlled and uncontrolled factors and parameters. Some of them are purely technical in nature, but the most dominant ones are financial and even human factors. The full spectrum of maintenance choices is very large, plus the cost can vary from zero up to the equipment price or even much more. Figure 1 illustrates an example of trade-offs regarding investment in oil analysis to prevent transformer failures.

> **Sometimes the cost of the tests and maintenance can be higher than the price of the equipment itself**

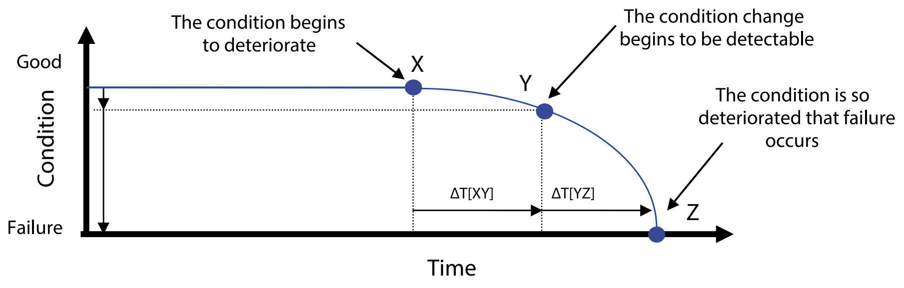

Figure 2. Theoretical transformer condition degradation [1]

> **Failure of even a small percentage of transformers is inevitable and cannot be prevented in any case**

2. Optimizing transformer maintenance

The transformer is a particularly sophisticated and tricky piece of equipment. It is an indispensable part of the modern industrial development and its failure may affect not only the transformer owner, but also many other parties, from the environment authorities through industrial producers down to regular electricity consumers. The price of the transformer failure can be very different from the unit’s real cost. Also, the owner has to consider the availability of a spare unit and the time from failure to replacement.

The transformer procurer and transformer owner have to consider many known and unknown factors from the design stage performed by the qualified supplier down to installation. After energizing, the owner has to consider what type of maintenance the transformer will need. This is the critical stage for optimizing the investment.

When planning transformer maintenance, most transformer operators visualize the famous scheme cited in many papers, presented in Figure 2. The original picture does not include the red lines, of course.

The main issue with this model is that 98 % of transformers do not fail, i.e. this model is applicable to less than 2 % of the population while 98 % of transformers end their life without any dramatic incident and they retire due to their age or for operational reasons. Deterioration of transformer’s condition and a transformer failure in most cases have no direct correlation. After the failure, it is obvious that the condition has already deteriorated, but not necessarily vice versa.

The main reason for a transformer failure caused by insulation issues is abnormal loading or external short-circuits. Most transformer failures are due to external reasons.

The distribution of different transformer health conditions is described in Figure 3.

This is a typical distribution of the transformer condition in a usual fleet, determined in accordance with the observed failure rates of different rated transformers operated by utilities from different countries in the period from 1968 to 2005 [2].

What can be read from Figure 3 is that 98 % of transformers will not fail; 1.5 % will have a minor failure, which can be detected by different tests or protection devices such as Bucholtz, GTPT or relay. Only 0.5 % of transformers will eventually fail. So, the transformer owner will have to pay for the maintenance of the entire fleet only to reveal less than 2 % of candidates for failure. The engineer responsible for transformer maintenance and procurement has to realize that failure of even a small percentage is inevitable and cannot be prevented in any case.

Also, a too expanded maintenance, tests or treatment can cause more damage to the insulating materials than actually prevent the potential failure. For example:

- Offline oil test: if applied too frequently, it can dramatically reduce the oil volume and expose the active part. Also, air bubbles can form inside the transformer and disturb the electric field which may induce failure.

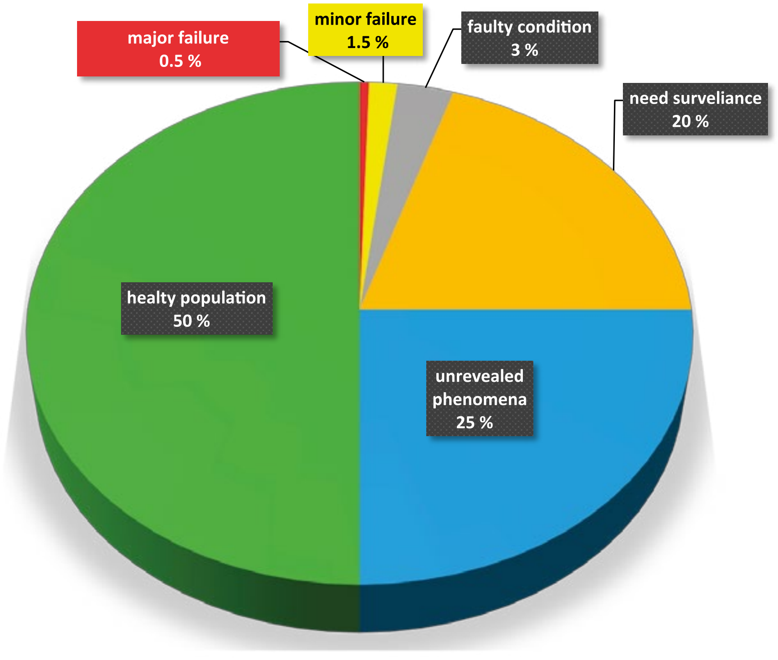

Figure 3. Transformer fleet health distribution [1]

- Online oil treatment: some oil treatment machines may leak and introduce air bubbles and in some cases, trip the Buchholz relay or in worst case cause failure. Other machines may cause the oil to overheat, changing its properties and even making it very corrosive to copper or silver.

- If applied too frequently, electrical test may affect the electrical insulation or even compromise it by applying unusual electrical fields and forces.

- Of course, online monitors of all types can frequently trip due to false alarms, and if there are too many false alarms, then there is a risk that the real alarm will not be taken into consideration.

In CIGRÉ's intensive study [2], there is a table presenting transformer failure sources which makes it clear that the main sources of transformer failure are design and manufacture.

The main and most interesting facts that can also be obtained from analyzing most of the transformer fleet characteristics is that insulating oil failure cases are negligible compared to other cases. The most dominant causes of failure are the actions that were done before energizing the transformer.

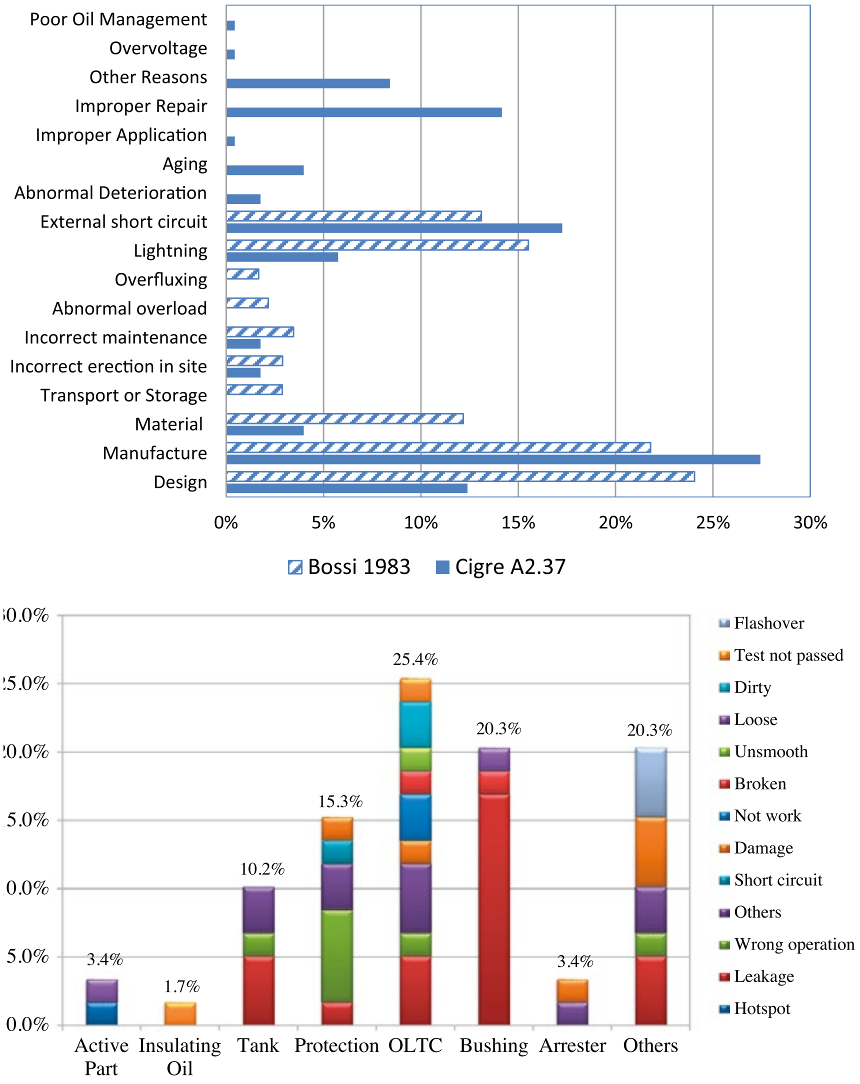

Figure 4. Literature survey of failure statistics [2], [3]

Table 1. Efficiency of different maintenance procedures

Tests and treatments for proper maintenance	Typical appearance during transformer life time of 25 years	Price per unit/ treatment or price of annual test	Relative cost of each maintenance in K$ for 25 years	Protection strength index	Efficiency index of each maintenance approach
Offline oil treatment*	3	20	60	10 %	0.2 %
Online oil treatment	2	15	30	40 %	1.3 %
Oil routine test	25	0.2	5	20 %	4 %
DGA	25	0.1	2.5	50 %	20 %
Online DGA	2	10	20	70 %	3.5 %
Other online sensors	2	15	30	30 %	1 %
Offline non-chemical test	5	5	25	30 %	1.2 %
Furan tests	15	0.1	0.5	10 %	6.7 %

**Offline oil treatment is only applied when online treatment is not available*

> **There is no clear evidence that any specific maintenance policy can really assist to reduce failure**

Table 1 describes various types of maintenance with their roughly evaluated cost and estimation of failure probability if the respective maintenance procedure is missed. Based on this, profitability of each of the procedures is assessed and shown in the last column.

Definition and evaluation of the failure rate are based on too many assumptions. The correct failure rate can be calculated if all units in the fleet were made by same design, and we know the total number of the fleet, the lifetime of the entire fleet and of course the number of failures related to the population and time of operation. But normally this is an impossible assignment. Calculating the number of failures in each year divided by the total population will also not be accurate enough because the failures can be from any of the transformer vintages, designs and manufacturers.

Another problem is that although the transformer failure rate is a very popular issue, it is not easy to find a comparison for the failure rate of transformers with specific maintenance strategy with a similar fleet and different maintenance strategy. There is no clear evidence that any specific maintenance policy can really assist to reduce failure. Service providers and equipment suppliers provide many theoretical models to demonstrate the efficiency of their product to increase reliability, but it is not realistic to have twin transformers with different maintenance strategy and to observe the differences with and without the proposed technology. Even for DGA, if the gases are abnormal, the transformer is open, and the phenomena are revealed and fixed, it is not always obvious whether the transformer was really rescued. In most cases, it is a matter of making an educated guess to understand what will happen if DGA does not reveal faulty condition. So, it is only a matter of belief and being convinced that any strategy or product can have a real positive impact on the transformer life span. In general, there are more false alarms from any measurement than real salvage.

Tables 2, 3 and 4 show two examples of extreme values of oil tests performed on transformers in operation.

> **DGA remains the principal tool to detect any internal issue if reliable sampling and measurement procedures are applied**

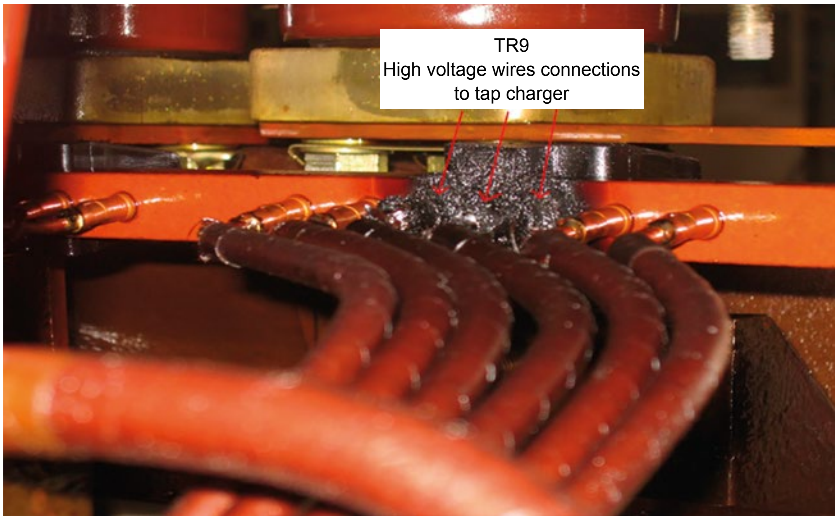

Figure 5. High DGA values without an interruptive failure (a failure causing interruption to the transformer operation) for the industrial transformer of 2.5 MVA

From this we can probably conclude that not all DGA tests or all routine oil analyses will always indicate an incipient failure, while without those tests the transformer may have a premature failure. Also, furan compounds are not indicating aging and imposing oil replacement [4].

3. Relative efficiency of some tests and treatments for transformers

Each treatment and test has a different cost, frequency and efficiency. All those parameters are summarized in Table 1. This table displays an average cost of tests and treatments based on regular international estimated prices on the ratio scale. The protection strength is an evaluation of the chances to prevent failure, if the tests are applied correctly. The efficiency index is based on the cost vs. protection strength. The profitability of major approach is relative to major products and technology available in today's market. Despite the conservative nature of this industry, the progress in treatment and monitoring is quite impressive, as is the improvement or alteration of materials and technologies.

Based on Table 1, the transformer owner is probably able to plan which technique to adopt for an average normally energized transformer. Of course, for special units such as nuclear plant transformer or a furnace transformer, or for non-redundant units, a specific approach will be used accordingly. The logic behind the „protection strength“ is not the efficiency of oil treatment or the accuracy of sampling and tests, but only the impact of a specific property that the method measures or deals with. Although it is assumed that the treatments and tests are performed by advanced technology and experts, the negative influence of some tests and treatments is also taken into consideration.

The modern well designed and manufactured transformers are less susceptible to moisture ingress, but DGA remains the principal tool to detect any internal issue. Of course, under the condition that sampling and measurement were performed correctly. Besides the positive aspect of online devices, the huge amount of data that they collect makes it a big challenge to dig out a real and true sign of an evident malfunction.

Table 2. Unusually high DGA values without an interruptive failure (a failure causing interruption to the transformer operation) for the industrial transformer of 2.5 MVA, manufactured in 1986; data taken on 24/07/2004

Gas	CO_2	C_2H_2	C_2H_4	C_2H_6	CH_4	CO	C_3H_8	H_2	O_2 (%)	N_2 (%)	TCG	TG (%)
PPM	15,719	12	54,099	36,260	18,735	1,384	4,713	888	0.79	6	111.38	17.98

Table 3. Extreme oil test values for a very old and still operating unit: a 24 MVA transformer manufactured by GE in 1961; oil weight – 15 ton; loading condition – approximately 50 %

Date	DPBC (%)	Dissipation factor	Breakdown voltage (kV)	Acidity in KOH (mg/gr)	Water in oil (PPM)	Total furan (PPM)
01/02/1999	0.1	0.02	62.7	0.1	16.4	0.7
12/12/2004	0	0.03	18	0.22	25	1.8
01/04/2011	0	0.04	50	0.4	32	2.2
01/04/2013	0	0.06	39	0.46	42	2.8
10/02/2015	0	0.04	30	0.5	46	3.8
10/01/2017	0	0.07	33	0.56	67	4.2

Table 4. Extreme oil test values for a very old and still operating unit: a 24 MVA transformer manufactured by GE in 1961; oil weight – 15 ton; loading condition – approximately 50 %

Sampling point	Bottom	Bottom	Bottom	Bottom	Bottom	Bottom	Bottom	Bottom	Bottom
Sampling date	**19/12/2004**	**11/01/2006**	**05/03/2007**	**12/02/2008**	**10/08/2010**	**15/04/2012**	**26/05/2014**	**6/1/2016**	**09/03/2017**
Carbon dioxide CO_2 (PPM)	6683	7729	8313	8365	3285	7677	5230	6377	5361
Acetylene C_2H_2 (PPM)	1	3	1	0	0	0	0	0	0
Ethylene C_2H_4 (PPM)	98	77	74	44	16	23	51	40	42
Ethane C_2H_6 (PPM)	43	42	47	52	32	53	166	144	173
Methane CH_4 (PPM)	81	82	78	85	51	66	57	101	105
Carbon monoxide CO (PPM)	1061	1213	1253	1415	587	1087	615	830	775
Propane & propylene (PPM)	158	241	195	91	118	213			
Hydrogen H_2 (PPM)	243	248	205	219	122	280	30	75	79
Oxygen O_2 (%)	0.2	0.2	0.3	1.1	0.7	0.1			
Nitrogen N_2 (%)	5.2	6.9	6.4	9.7	4.4	4.2			
Total combustible gases (PPM)	1527	1665	1658	1815	808	1509			
Total gas (%)	5.4	7.1	6.7	10.8	5.1	4.3			
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> **Maintenance policy is driven by economic aspects, consequences of power outage, insurance companies, and the knowledge and beliefs of the transformer owner**

4. Main maintenance strategies for transformers

Maintenance approaches are part of the main maintenance strategy, and they can be adopted or not, according to the chief maintenance policy. This policy is driven by economic aspects relating to the transformer and consequences of power outage, insurance companies, as well as the knowledge and beliefs of the transformer owner and the responsible engineer. During the transformer life, the maintenance concept can be improved based on the learning process of the staff.

Table 5 lists the most common strategies applicable to any transformer. Of course, the best option is to combine and fine tune according to the specifics of each case, the loading, manufacture, policy, etc. In most cases, the adopted maintenance strategy is based only on the worst-case scenario. It is better to evaluate the probability of this scenario and not rely only on premeditated concepts.

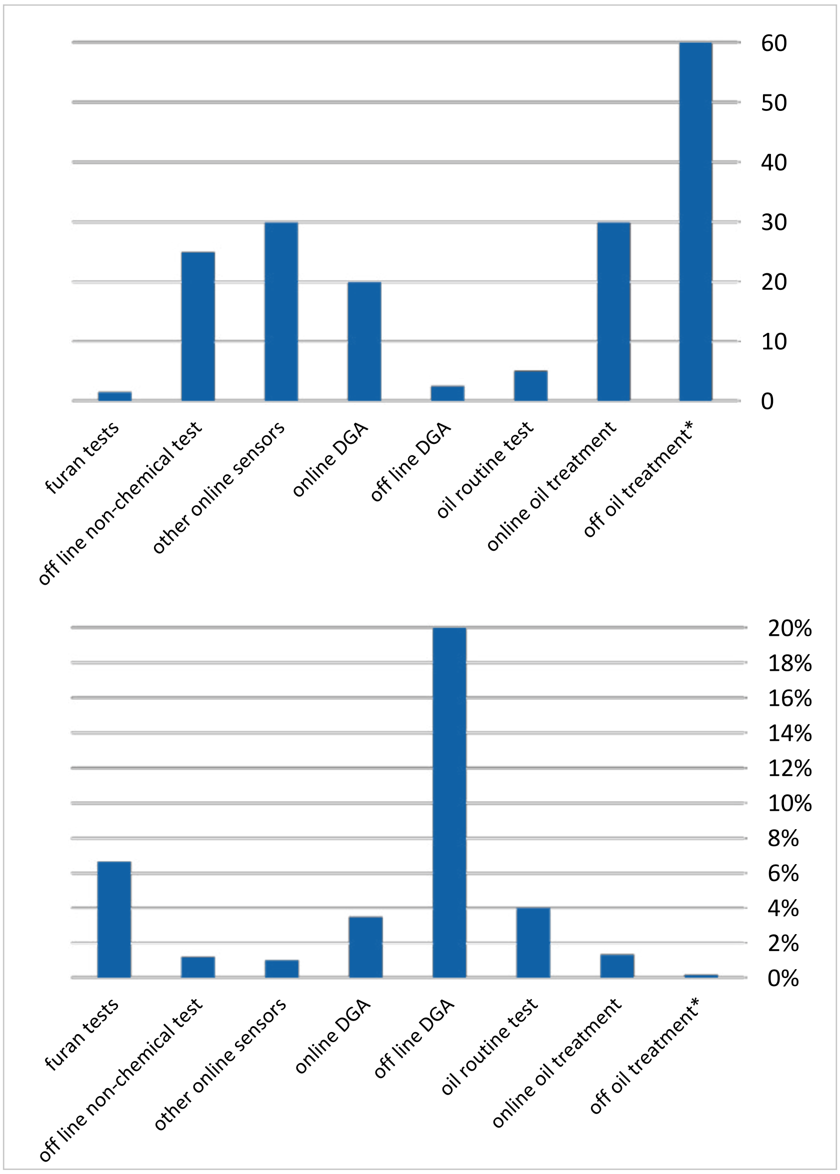

Figure 6. Relative expenses of maintenance in K$ (top) and efficiency index of various maintenance procedures (bottom) applied for 25 years of exploitation of an average transformer

The principles of each of the strategies along with their pros and cons will be explained in detail in the next column.

Conclusions

- Performing all the tests and treatments will not lead to a safer and longer maintenance.
- Run-to-failure is a realistic option for most transformer types, except if transformer is vital and/or cannot be replaced. Each case has to be analyzed carefully and continuously.
- Instead of spending on expensive tests and treatments after energizing, it is always better to have a very careful specification and design adapted to each circumstance.
- After the inspection and audit of the manufacturing process, it is crucial to adequately prepare the transformer before it is energized. These are crucial phases to ensure reliable and economical exploitation of a transformer within any maintenance strategy.
- The tests proposed in the standards and literature are only a recommendation. The most cost-effective test for transformers is to periodically run a DGA test applying a reliable procedure. Other techniques may also be applied to increase reliability, but they are less cost-effective from the maintenance point of view.
- Suppliers try to convince the users to adopt their treatments and tests in order to avoid failure modes by presenting transformers that failed in the past. Adopting a specific approach to testing and/or treatment can sometimes be more expensive than a cost of 1 % failure probability for the entire fleet. On certain occasions the failure can even be reduced to zero just by eliminating the external factors.
- Adoption of an intensive and aggressive test and treatment may reduce the transformer life. It is crucial to evaluate each case separately and not make one decision for the entire fleet, even if the fleet consists of only two transformers.

Table 5. The main maintenance strategies

Principal maintenance options					
Preliminary maintenance	Tailored maintenance	Over maintenance	Partial maintenance	Full tests and treatments portfolio	Breakdown maintenance

The transformers are not identical, and they do not behave identically, not even twin transformers.

- Offline DGA is the most cost-effective method to reveal malfunction, repair small defects and extend transformer life. The main condition of real efficiency is to have the measurements and diagnosis performed according to the latest principles, such as those cited in [5]. Also, having a dedicated expert is always a better option.
- In general, a huge investment in different oil treatments has proportionally less influence on the extension of the transformer life. Of course, in some cases this is most welcome, but for most transformers such investment may be placed in other direction, which would be much more beneficial.

One of the next columns will present a comparison between the fleet condition with and without regular oil treatment, offering more cases of DGA and oil results.

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[5] *Recent Developments in DGA Interpretation*, CIGRE Technical Brochure 296, 2004

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