An accurate and customized health index is possibly the best maintenance strategy to have for a large transformer fleet

ABSTRACT

Nowadays, trendy attempts to avoid transformer failures include life assessment programs, software and health indices. Although many efforts are invested in these approaches, the transformer failure rate is not significantly reduced. This article will highlight the main critical points that have to be taken into consideration when index and life assessment is concepted and evaluated. The more details are taken into consideration and the more deeply they are treated, the more representative and accurate the health index will be. An accurate health index is probably the best maintenance strategy to have for a large transformer fleet, and it may be ingrained in the mind of any human interdisciplinary expert, or in the code of an artificial intelligence software.

KEYWORDS

health index, maintenance, life assessment

Health indices and life assessment methodology

Myth, fake maintenance or genuine contribution to transformers fleet reliability?

1. Introduction

Transformers are a very important piece of equipment, vital and crucial for the functioning of a modern society. As the population and industrialization growth impose the use of higher voltage and higher power, with units occupying less room and using fewer insulation materials, modern transformer design is in many aspects quite different to transformers made 20 years ago.

In the post-privatization era, the redundancy of transformers has decreased substantially, so in case of a transformer failure, the impact for the final customer or stakeholder has grown bigger. The cost of power transformer monitoring and maintenance has become negligible in comparison to the cost of failure consequences. Transformer owners and engineers are willing to understand the failure mechanism, mainly to avoid a huge cost of power outage and eliminate replacement or repairing intervals, while papers, brochures and academic research on power transformer maintenance, survey and life assessments have become best-selling literature and preferred conference subjects [1, 2].

2. Using health index and life assessment strategy for power transformers

One of the applied strategies to prevent failures of the most vulnerable and critical transformers is to use assessment approaches or attribute a health index to the fleet. Such software and programs have been present in the literature for more than 20 years and over the last 10 years they have also become predominant as a commercially widespread product. Many shareholders attribute to these models and software the ability to successfully replace the expertise of human transformer experts.

Transformer stakeholders have to consider a few important issues.

- The transformer design, material and technology are in continuous development and they are always a few steps ahead of a diagnosis and health index criteria considerations. And this is not only due to commercial issues.
- If one health index program is working well for a specific utility or transformer fleet, it is not necessarily adequate for others.
- While the analogy between the transformer diagnosis and human medicine is well intentioned to help understand the idea, in reality, human medicine is incomparable to transformer diagnosis due to many reasons, among them the fact that all humans are of the "same manufacture", same raw materials, same functioning, etc. Fig. 1.
- The investment in the research of diagnosing and prevention of human diseases and faulty conditions is incomparable higher than that in the research of transformers. The medicine of the 21st century is able to successfully confront most of the viral and natural diseases today, but not so much the artificial diseases. Nevertheless, even in the human medicine there is still no reliable health index or life assessment for the homo sapiens.
- Only highly evolved and invested artificial intelligence (AI) may theoretically attempt to replace the diminishing role of human experts in transformer maintenance. The gap in knowledge resources between human experts and AI is still significant.

Figure 1. Unlike humans, transformers are very different. Having one concept for their health index is incorrect.

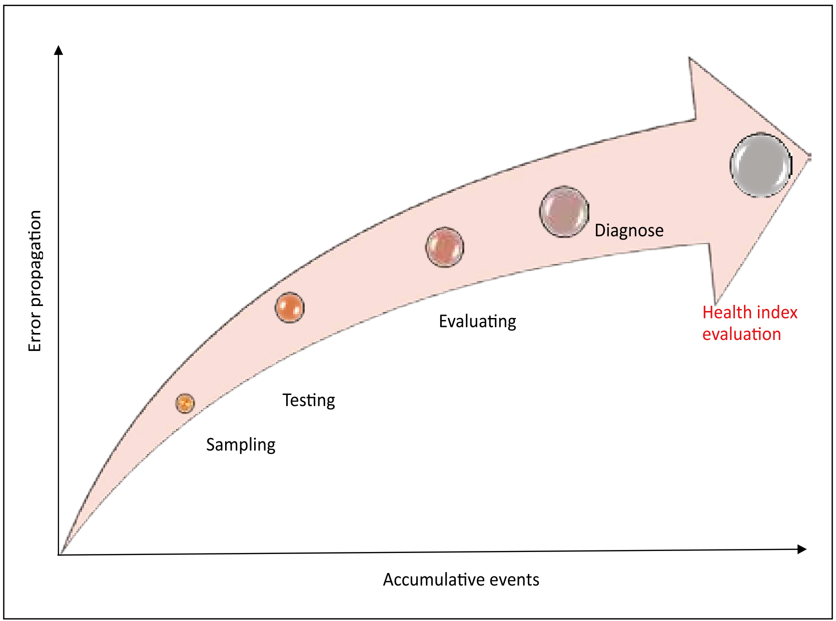

Figure 2. Each maintenance event increases the uncertainty of the health index evaluation

In the post-privatization era, the redundancy of transformers has decreased substantially

- Establishing a strategy and investments based on the existent health index and even AI programs momentarily poses a higher risk for transformer's operation than random failures or breakdown maintenance, Fig. 2.

The following stages of transformer life assessment or health index are an additional stage to the other four classical phases used for power transformer diagnosis:

1. Oil sampling and information gathering
2. Oil or transformer properties measurement or analysis
3. Establishing transformer diagnosis according to the measured data
4. Health index creation, analysis and using measured parameters for the entire fleet
5. Continuous and regular decision making about transformer operation or replacement

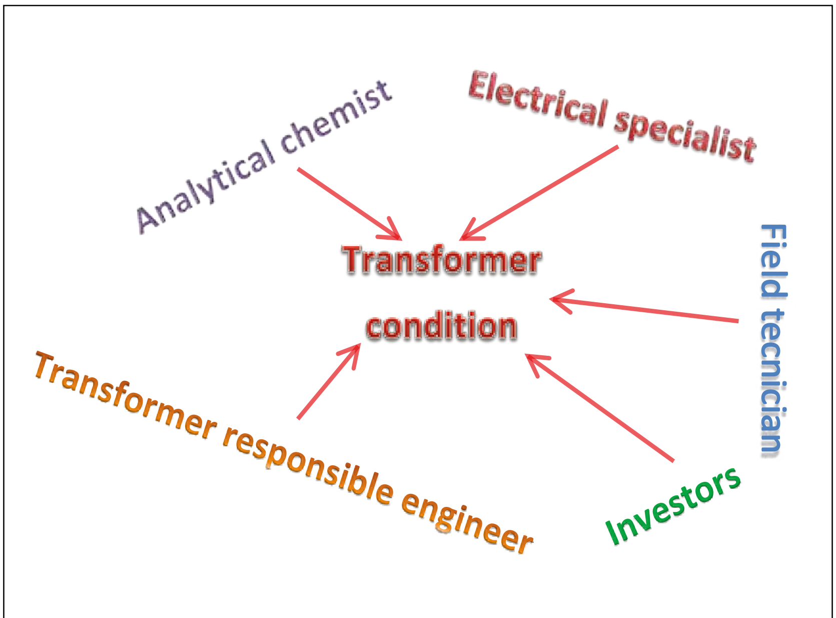

Figure 3. Interdisciplinary collaboration is the optimum path to establishing transformer's condition

The phase number 4 is an added concept, not a necessary step, intended only to ease the decisions of the operational mode of the transformer. It may only clarify the functionality of the entire transformer fleet.
Other alternative maintenance approaches include:

- Breakdown maintenance. This optimum scenario recommends investing in good design, manufacture and energizing without any further actions until the replacement of the unit at a certain age, e.g. after 25 years. This strategy may save budgets without the need for any sampling, tests, diagnoses and assessments or health index complications.
- Diagnosing each transformer by performing all the tests and comparing the data with the existing standard limits only. While performing this diagnosis is simple, the cost of false or missed failures may be considerable.
- Human expert diagnoses in a brainstorm including electrical and chemical experts and a responsible transformer engineer. This is the best way to define the right strategy and a health index personalized to the specific fleet, considering as many aspects as possible, Fig. 3. Unfortunately, this approach has become rare. This model is proved to be successful [3], as shown in Table 1. In this example, two years after the health index was created, two transformers with the health index of 1 (marked in red colour) were repaired after intensive chemical and electrical measurements.
- Lack of human experts with the need to asset ranking to an entire fleet, impose the using of health index to have a correct view on overhaul transformer condition. Many commercial companies and many big organization that have to assure a continuous power supply through many transformers, develop such programs. In last decades also the artificial intelligence complex mathematical models, different software, etc. [4]

Despite these investments and efforts, transformer failure rate remains constant [5] or only slightly reduced. Transformers continue to fail, but perhaps the worst side effect has become the number of false alarms that impose substantial unnecessary investments. Most programs use traffic light signalling to distinguish among green, yellow, sometimes orange, and red indicators, Table 2. While such

Table 1. Transformer condition assessment based on oil tests (relative values)

	UAT 30B	UMT 30B	UAT 30A	UMT 30A	UAT 40B	UMT 40B	UAT 40A	UMT 40A
Acidity	5	3	5	5	10	5	6	5
Furan	6	3	6	7	10	4	6	7
Ethylene C_2H_4	3	2	3	10	3	2	3	6
Acetylene C_2H_2	3	2	3	8	-	2	3	4
Methane CH_4	3	2	3	10	6	2	3	4
CO_2	4	6	4	4	5	3	5	10
UAT rank	4		3		1		2	
UMT rank		3		1		4		2

presentation may be attractive to the eye, it is not that useful since the model is too simple to be able to discern between real faults, normal behaviour and false alarms. In most cases, the error for determining the correct condition of the machine is that it covers the entire range between "red" and "green".

Most of commercial software notify that this is only a recommendation and the uncertainty of results is not negligible. The original idea of these models was only to advise or assist the decision makers, but in reality, in many cases the recommendations of HI models are taken directly as an absolute truth.
Occasionally, with some health index programs the transformer shareholders are faced with a frustrating situation of a failure of some units which are not included in the highest priority risk list. To not investigate high-risk units might be a favoured economical decision. For example, in 1999, in a fleet of more than 500 transformers, 22 units were found to have abnormal oil limit values. Although no special maintenance or treatments were done on these transformers, all of them operated without any problems until 2016 when one unit failed due to unusual loading [6]. However, during the same period another unit failed due to excessive moisture although there were no previous signs of alarm, Fig. 4.

Table 2. Traffic light signalling used by most health assessment software

Bad
Poor
Average
Good

The gap in knowledge between human experts and AI is still significant

This is probably the main reason why there are so many commercial software and models presented in the literature and available on the market, trying to cover the gap between the expectation and reality, as described in [5].
Another issue is that the definition of transformer failure is quite ambiguous. Different studies, research and insurance companies have a different view on what a transformer failure is. From the user's point of view, transformer's condition can be categorized into the following four states:

1. Healthy transformer – a unit that can operate without any intervention until their normal end of life.
2. Faulty transformer – a unit undergoing minor malfunctions at an early stage that can be repaired on site.
3. Failed transformer – a unit that failed with a total loss damage and is beyond repair. The trip due to failure can be triggered by any monitoring device, such as Buchholz or differential protection.
4. Catastrophic transformer failures – transformer failures that occur suddenly and cause damages to the environment or have a substantial impact on power supply.

It is very important to use one terminology for these states to be able to monitor different types of faulty conditions. The accurate health index program must be able to display an improvement on faulty condition, and to approve the current maintenance policy over at least 20 years. The failure rate evaluation is highly dependent on the failure definition and period evaluation, Table 3.

3. Improving health index parameters

It might be possible to substantially improve the efficiency of health index and life assessment issues by imitating, as much as possible, the entire set of con-

Figure 4. The failed transformer due to excessive moisture

Transformers are a very important piece of equipment, vital and crucial for the functioning of a modern society

siderations and judgments that a chemist, an electrical engineer and a transformer maintenance expert have. These programs should accumulate the data over the years on as many transformers as possible. Commercial bias of software producers is undesirable.

The following are some of the main criteria that are probably missing from today's health index programs.

3.1 Oil analysis factors

Oil analysis is a major monitoring tool for diagnosing transformers in operation. All oil tests may and must be performed when the transformer is energized. Only the oil samples taken from an energized transformer can represent as many internal malfunctions of the transformer as there are present. The main factors to be taken into consideration in relation to oil analysis are sampling ambiguity and oil test ambiguity.

3.1.1 Sampling ambiguity

While oil sampling is considered to be the most low-tech stage for transformers assets, it is the most crucial and unfortunately the biggest source of uncertainty. All health index and life assessment programs should be governed by sampling quality. Some factors that should be improved include the following:

- Sampling should be taken only by well-trained, well-experienced and open-minded technicians. Sampling oil from transformers is subject to many small details that can have a huge impact on the sampling quality and the whole diagnostic process.

Table 3. Variation of annual failure rate over a time period

Period of failure rate evaluation	Annual failure rate
25	0.83 %
20	1.18 %
15	0.84 %
10	2.78 %

Different studies, research and insurance companies have a different view on what a transformer failure is

- Samples should be taken, as much as possible, following the same procedure, using the same vessels and if possible by the same team.
- Sampling vessels. Oil samples can be taken into anything from soft drink plastic bottles to sophisticated glass ampules or syringes or metal bottles, Fig. 5. All those types of vessels may affect the oil test and the transformer condition. For example, the oil kept in plastics will have a higher moisture content and low breakdown voltage, which may compromise the transformer oil sample.
- The oil drained from the transformer before the actual sample is taken should be systematically of the same quantity, and adequate to the transformer size. But in no case can it be less than 0.5 litre or more than 3 litres. One of the recommended ways to assure that the oil is representative is to use a portable relative moisture device, so that the oil from the transformer flows through its sensor to the bottle or syringe. This will ensure that the samples are taken only when both parameters are stable, Fig. 6.
- Sampled oil temperature should always be recorded, even using a small hand thermometer. Also, the top oil temperature is very important in some oil tests, mainly for determining the gases and moisture solubility.
- Labelling oil samples. The task to write something in the oil-contaminated area is quite challenging. Although everyone tries to adopt a sophisticated labelling system, in large batches of samples, there will always be one or two that are incorrect. Even the most pedant human will make a mistake, especially when working in extreme conditions such as excessive heat, smell and oil vapour.
- Oil samples should be transported to the lab as fast as possible in dark container, which should not be shaken, broken or damaged. Today in the outsourcing era, the distances from the transformer to the lab have increased substantially. Transformer owners do not base their choice of the outsourced lab on the time elapsed between the sampling and arrival at the lab. Sensitive oil samples should be transferred through customs in pressurized chambers before air transport. These journeys can take much longer than expected due to the customs procedures and can be exposed to extreme pressure. Sometimes to keep a syringe intact is a very complicated issue. Commercially available standard syringes are sealed with special silicone and still limited to a very short shelf life. Regular syringes that are not subjected to special treatment are even more susceptible to transport conditions.
- The most recommended solution for transformer oil sampling is to pass an accreditation process, such as sampling of flue gas for environmental purposes. It might seem uneconomical at first to conduct expensive sampling, but in the long run this is a much cheaper option than covering the cost of the consequences.
- Sampling intervals and the time elapsed from the previous sampling are very important to any health index. If a health index is calculated on the basis of the test results obtained once in five years, and the last test was conducted four years ago, the meaning of the value will

Figure 5. Different vessels for insulating oils

All oil tests may and must be performed when the transformer is energized

Figure 6. Preparation for oil sampling

be quite different from the data that is obtained once per year or biannually.

- One of the problematic practices of sampling technicians and laboratories is to resample if the first oil sample oil did not yield acceptable results. If the second oil sample receives better results, this does not mean that the transformer is in better shape. It only means that the sampling procedures and team are not mindful enough. The sampling standards IEC60457, ASTM 3613 and ASTM D923 define a certain oil volume to flush and a procedure for obtaining oil in bottles and syringes.
- The oil sampled from a different valve or flushing too much oil will fill the sampling vessel with the oil that is different than the oil intended to be tested and compared to any limits or trends, Fig. 7.

3.1.2 Oil tests ambiguity

Oil tests carry important weight on all health indexes and life assessment modules. The ambiguity of the values obtained by oil tests is theoretically high due to the lack of standardized materials, and this is true for almost every test. As in all other aspects, in the post-privatization era and very tight price bids, the cost of oil test packages has become a major parameter for selecting the service supplier. The laboratories that invest in research and quality gradually disappear if they are not financed by another profitable activity. Due to commercial stresses, it is a viable possibility that uncertainty of oil tests will increase and in the next future become even higher. The uncertainty of oil tests is propagated directly through the entire assessment process and amplifies the uncertainty of ranking transformers by any health index or model, even if the users or developers of such models refuse to admit so. The uncertainty of oil tests may be a consequence of various factors:

- Different test methods used. Officially, oil tests are performed according to two main standards, ASTM and IEC. While both these standardization bodies are international, in reality the world is divided in two when it comes to their application, with each being used in one part of the world. Besides, there are also national standard methods that are used locally. The differences between IEC and ASTM methods are outlined in Table 4.
- Different implementation of approaches from the same standards. Even at a laboratory, when implementing a specific standard method different ways and instruments are used. In fact, almost every laboratory implements its own method which is mainly based on the instrument manufacture and both on traditional and historic perspective of each laboratory. The absence of standard materials with known values for oil tests prevent real control and accuracy evaluation. A non-chemist specialist has to refer to all test results as a value that expresses the oil property along with the laboratory efficiency, accuracy and repeatability, even heritage. The percentage of all these aspects in the final figure is not defined and is unclear.
- Interpretation of results. Beside the uncertainly of methods and test performance, there are different methods for determining if the measured figure refers to the good, medium or a faulty state of the transformer. Different standards have different limits, such as IEC and IEEE, while other standards are also different in respect to some important tests. Moreover, even within the same standard, the limits change over time. One of the best examples is the acidity


Figure 7. Same valves, but different opening may yield different results

limit, which was defined by IEC60422, 2nd edition, 1989 [6] as 0.5 mg KOH/litre until 2005 when the value was decreased to 0.15 mg KOH/litre or even lower. In cases like this, all health index programs have to be updated. This also gives rise to a philosophical question: Do old design transformers fit to the old or new standard limits? Many other tests face similar problem, but the most important and contradictory limits are those for DGA, as shown in Figure 8.

The preferred approach for obtaining representative and correct limits for each test is to calculate the limit for 90th or 98th percentile as a pre-failure value; or to follow the trend and decide in each case and for each transformer and parameter the suitable critical moment for taking action. It is also crucial to know that the trend of most of the oil parameters is not linear at all; any attempt to obtain linear extrapolation is ineffective. The health index for each chemical parameter should take into consideration the non-linear scenario.

Conclusion

In conclusion, let me note that this article represents only the viewpoint of its author. In my next contribution, I will discuss and present the main sources of inaccuracy for several oil tests, from sampling to diagnosis to ranking, using any methodology. The main concepts that will be proposed

Table 4. Comparison of the main IEC and ASTM oil tests

Parameter	Test type	IEC	ASTM	Compatibility
Breakdown voltage	Routine	IEC 30156	D1816 in service D877 new oil	No, different test conditions
Water in oil	Routine	IEC 60184	D1533	Yes, partially, dependent on the top oil temperature
Acidity	Routine	IEC62021-1 Potentiometric IEC62021-2 Colorimetric	D664 Potentiometric D974 Colorimetric	Partially, different tests conditions, but results of the same scale if the tests are properly performed. No absolute method for acidity.
Dissipation factor	Routine	IEC60247	D924	No, different test conditions
Antioxidant content	Routine	IEC60666	D2668	Partially
Interfacial tension	Complementary IEC Routine ASTM	IEC 62961	D971	No
Corrosive sulfur	Routine IEC ASTM special	IEC 62353 & DIN 51353	D1275 B probably to be revised	No. Both standards are still searching for a more accurate method. IEC is more representative.

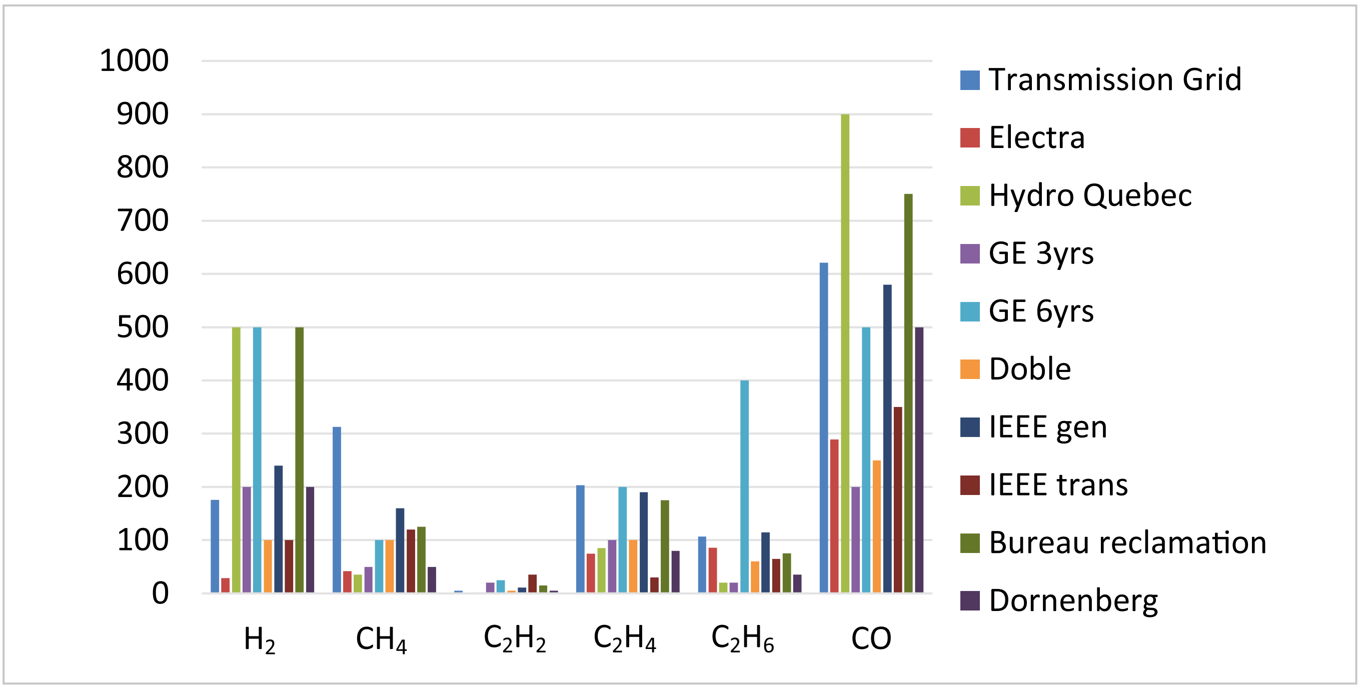

Figure 8. Different limit values for DGA from different sources

Oil tests carry important weight on all health indexes and life assessment modules

and substantiated include the following. Increased inaccuracy of each stage prior to devising health index programs will definitely degrade the condition of the transformer as defined by health index, even the measured values are within the limits of current standards and guides. The total uncertainty that evolved from the sum of all uncertainties is well above 100 %. Without considering the gathered errors, the actual state of transformers can be good or bad without a real possibility to discern between the two states. Without being aware of all these aspects and making all efforts to reduce the errors as much as possible, the diagnosis and life assessment by artificial intelligence or any other mathematical model is in fact ineffective. Still today, a diagnosis by an open-minded human expert will always be superior to any artificial intelligence or health index, even in the case of allegedly intensive actions, such as performing expensive tests and implementing sophisticated and costly health indexes. Also, theoretically, it there will always be a significant gap between the developments in the transformer technology, materials and concepts and application of those vulnerable issues to the life assessment programs in particular. Artificial intelligence will be able to compete with human expertise only by accumulating all of the open and restricted data, and all of the knowledge available. Considering that most faulty conditions do not lead to failures, health index methodology may induce false alarms that cause unnecessary investment or even transformer replacement while hiding real evolving failures.

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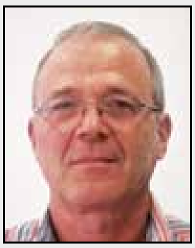

Marius Grisaru received his MSc in Electro-Analytical Chemistry from Israel Institute of Technology in 1991. The same year he joined Israel Electric Corporation (IE) and established the insulating oil test policy and methodology in Israel. He now performs insulating oil tests and oil treatments in Israel for IE and other local industrial and private customers, as well as trains and educates electrical staff on insulating oil issues. Marius is an active member of IEC and CIGRÉ, and a former member of ASTM. He is the author and co-author of several papers, CIGRÉ brochures and presentations on insulation oil tests, focused on DGA and analytical chemistry of insulating oil.