# Condition and risk assessment of power transformers:
# a general approach to calculate a Health Index

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**Abstract**

Power transformers are the most important assets in substations and play an important role in the reliability of electrical systems and in the quality of the energy delivered. As the population of transformers in service is getting old, much attention must be focused on transformers availability and reliability. So the condition and risk assessment of the transformers are more and more important to improve the transformers performance, extend their useful life, to decrease costs and to take the best technical and economic decisions, concerning their life cycle management. The "Health Index" was developed to assess and classify transformers based on their condition and to support decisions, concerning refurbishment and replacement. The basic concepts associated to the "Health Index" and to its calculation method are explained here, in a summarized way. An example of the application of this method to a transformer is also given here. Finally, the advantage of the combination of this index with the "Criticality index" is also highlighted.
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## 1. Introduction

The lack of regulation in the electricity market has led to new challenges for the electrical industry.

Increased transformer use, deferred capital expenditures and reduced maintenance costs are the main challenges the electrical utilities are facing nowadays. Thus, the condition assessment of equipments plays an increasingly important role, in fuelling the right decision, regarding the life cycle of the transformers: supervise, refurbish, relocate, or replace.

In fact, an increased demand for improved financial and technical performance of power utilities has pushed the asset managers to better assess the condition of their transformers.

To optimize the balance among capital investments, asset maintenance costs and operating performance (high reliability), there is a need to provide economic and technical justifications, for engineering decisions

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(on investments needs and maintenance programs) and also for replacement plans [1].

The transformer is a multivariable system, comparable to a living being, built with many different materials, such as metals (for example: copper, iron, zinc, silver), varnishes and glues, solid insulating materials (like paper, pressboard and wood), and liquid insulating materials like oil (which on its own has several hundreds of different components).

To make things more complicated, an energized transformer is exposed to electrical current that produces the Joule effect together with electrical and magnetic fields, with the presence of two harmful chemical products for transformer insulation: oxygen and water.

The oxygen that is present in greater concentrations in free-breathing transformers is still present, although in lower concentrations, in sealed type transformers.

The water can have 2 main sources: external, resulting from contamination, (water coming from outside of the transformer due to a leak) or internal, produced by oil and paper degradation.

Knowing that the ageing reactions (mainly hydrolysis and oxidation), are chemical reactions and the rate of

these reactions have an exponential dependence on the temperature, ruled by the Arrhenius law, it is easy to perceive the complexity of the transformer ageing process and the consequent uncertainty of any forecast, about its remaining useful life. Due to this scenario, it seems to be very important (in spite of also not being easy), to develop a system which provides credible information, about the level of degradation of a transformer based on as much relevant parameters as possible. The idea of this new approach is to associate to a transformer, a number that indicates its condition - for this reason, this number is called "Health Index" [1-11].

Using the "Health Index", it is possible to rank the transformers of an entire fleet, by their conditions. This became very important for electrical companies, because it makes possible to direct the maintenance budget, mainly to the units that are in worst condition and consequently have the highest risk associated to their operation.

## 2. Risk assessment

For risk assessment, it is necessary to identify and quantify risks and to build a risk management system. The risk assessment has several steps.
1- Identify risks.
2- Describe, analyse and quantify the risk scenarios.
3- Study consequences of risk scenarios, based on simulation, experience feedback, and expert judgments.
4- Classify and prioritize risks.


A risk has 2 basic components:

1- The frequency of occurrence of undesirable events. This frequency gives information on how often these events occur, but as we usually don't know this frequency, it can be replaced by the probability of occurrence.

2- The severity of the consequence of such events.
So, each transformer can be represented in a 2 axis diagram, where an axis represents the "Probability of failure" ("Probability factor") and the other axis represents the "Consequence of failure" ("Consequence factor") [1].

The "Probability factor" – involves analysis of the historical data of the transformer itself and of other similar units, including the statistical data of the specific parameters that can contribute to the failure of the equipment, according to the experts judgment. It is important to mention, that it is not easy to

calculate this factor and its uncertainty is usually quite high.

The "Consequence factor" – involves the repair, or replacement costs of a transformer and also any other potential indirect costs, like for example: energy not delivered and costs of environmental contamination.
The Risk Index (RI), in a simplified way, is defined by the product of the "Probability Factor" (PF) by the "Consequence Factor" (CF)

$$RI = PF \times CF$$

### 2.1 Probability factor

The Probability Factor is calculated by developing a list of critical parameters and assigning to each one an index number and a weighting factor, depending on the importance of this parameter, for the transformer life.

Examples of critical parameters are the following ones:
- Operating history (overloading history).
- Failure history of "sister units".
- Oil testing history/Paper tests – Actual condition.
- Operating environment (exposure to system faults external to the transformer).
- Manufacturer (design, materials, standards used by the manufacturer and level of expertise and experience of people involved in the construction process).
- Age and service time that may affect mechanical strength, and so the ability to withstand short circuit forces, usual in a transmission/distribution system.

However, it is important to underline that, there is no single scientific method, available to determine the exact probability of failure [2], or to calculate the precise "end of life" of a power transformer.

### 2.2 Consequence Factor

The "Consequence Factor", that measures the severity of a failure, in terms of its effects, comprises:

- Undelivered energy.

- The maximum loss (cost of repair, considering also the availability of spare

parts, that can be used for repair), repair feasibility, or replacement costs, of the complete transformer, environmental and clean-up costs, lost revenues, litigation costs, or any other indirect costs, related on the transformer failure.

- The strategic impact of the transformer (for example: existence of critical customers and impact of loss of reliability).

The strategic impact is usually expressed by a "subjective" multiplier that must be developed by the asset managers, in close collaboration with the engineers of the utility.

So, the Risk Index of a transformer is a number that can be used to rank a global population of transformers.

Using Risk Assessment, the transformers can be listed and prioritized, but this does not identify the real condition of each individual transformer.

To do this, a condition assessment is necessary, involving for example, a calculation of the "Health Index" on any other "Condition Index", mainly based on the test results used for monitoring the transformers, along the time.

## 3. Condition Assessment

The main purpose of condition assessment is to optimize asset management decision making and risk reduction, over the equipments life cycle.

Suitable asset management practices require an understanding of the equipments aging phenomena, in order to allow to set up criteria, for asset life decisions and to select the right techniques for condition assessment.

Good maintenance practice and condition monitoring by chemical, physical and electrical tests, are key factors for an excellent asset management program.

Asset management includes maintenance, refurbishment and replacement, besides system planning aspects.

Asset management tries to achieve the required quality in service, in the most cost-effective manner, taking into consideration the best timing to make investments, avoiding unprofitable use, or obsolescence of assets, and minimising unacceptable business risks [1].

Oil monitoring provides the main operational information for reporting condition assessment of transformers. This information is used to apply preventive maintenance methods, to improve the reliability of the transformers and to extend their operational life.

In oil filled transformers mainly dissolved gas analysis (DGA) and moisture monitoring (lately, on-line monitoring) have played an important role, for asset condition assessment.

A practical tool, recently used for asset management is the "Health Index".

## 4. What is a "Health Index" used for?

The "Health Index" is used for assessment of the actual technical condition of a transformer, by quantifying the results of operating observations, laboratory and site testing and field inspections. The Health Index is the result of an evaluation that quantifies the condition of each transformer.

The "Health Index" can be used to rank a fleet of transformers, according to their technical condition, to establish, for example, capital spending priorities.

### 4.1 How to build a "Health Index"?

In a transformer, there are several subsystems which conditions are meaningful to define the global condition of a transformer, such as:

The windings, and the magnetic circuit (core), (usually called "active part", which is located inside the main tank of the transformer) the bushings, the cooling system, the preservation system, the tap-changer (usually an on-load tap-changer), and the protection system.

So, it is relevant for the condition assessment of the transformer, to know the conditions of its main components.

The calculation of the "Health Index" is mainly based on test data and operating observations available.

This Index is calculated predominantly using data coming from the periodic control tests and the history of the transformer (including the operating conditions).

Although there are several approaches to calculate this index, [2-11], the method we have used can be described in 4 main steps:

To calculate a health index, first it is necessary to collect the relevant information available, about all the transformers components, including the results of each individual test, performed on them.

Then, the results of each test are converted to a numerical score, which must be very well defined.

To assign a score to each value of each parameter it is necessary, a lot of expertise, in several fields, depending on the parameter to be evaluated, for example electrical tests, chemical tests, maintenance

procedures and so on, what is a task for a multidisciplinary team of experts.

The "Health index" of a transformer component is calculated by summing up the products of each individual score of each parameter by its "weighing factor", for all the parameters used to characterize this component.

So, to calculate the "Health Index" of a transformer, we must follow 4 steps.

*Step 1. - Define the parameters used for the "Health Index" calculation*

First, the parameters used for this calculation must be defined.

A non-exhaustive list of suggested parameters to be used for calculation of a transformer "Health Index" is the following:

For the transformer "active part" (windings and core), the following parameters are suggested [11]:

- DGA (Dissolved gas analysis) in oil
- Furanic compounds concentrations, in oil
- Oil tests, used to define the "Oil quality"
- Electrical tests (like for example: dissipation factor, capacitance, excitation current, winding resistance and insulation resistance (Megger).
- Infrared thermography
- Age
- Load profile/load history
- Maintenance history
- Grounding
- Corrosion.
- Other maintenance data (for example: visual inspection to detect the presence of oil leaks, in gaskets and seals).

In case of bushings, the parameters that can be used are for example:

- Type of bushing
- Age
- Condition of the insulators (visual inspection of porcelain, glass, or composite insulators)
- Condition of connectors
- Presence of leaks
- Power factor/Dissipation factor
- Thermography
- Capacitance
- Maintenance history.

In case of the tap-changer, we can consider parameters such as:

**-** Manufacturer

- Type
- DGA
- Oil quality tests
- Contact wear
- Maintenance history.

For the preservation system (conservator), the following parameters can be used:

- Visual inspection - Presence of leaks: Silica-gel and rubber bag/membrane
- Maintenance history
- Corrosion.

For the cooling system (radiators), we can consider, for example, the following parameters:

- Visual inspection and thermographic inspection:
    - Presence of leaks in pumps and in tubing
    - Fans
- Maintenance history
- Corrosion.

*Step 2. – Define how to rate each parameter*

Assign a score to each parameter. For example, in case of DGA, the corresponding score is calculated as a weighed average of the scores of all the sub-parameters included in that parameter. In this case the sub-parameters are the concentrations of the several gases analysed in the oil, by DGA.

The score of each individual gas ($H_2$, $CH_4$, $C_2H_6$, $C_2H_4$, $C_2H_2$, CO and $CO_2$) depends on the range of concentration to which the concentration value of each gas belongs. This score is assigned using a table built for each gas, where each range of concentration corresponds to a score (0 to 4).

The ranges of concentrations used to assign the scores to each gas are defined using the experience that supports the interpretation codes (IEC codes [12] and others, like the IEEE codes [13]).

On the other hand, the "weighing factor" for each gas depends on the importance of the information extracted from each gas, to define the condition of the transformer.

*Step 3. - Calculate the "Health Index" for each component*

The individual "Health Index" of a transformer component can be calculated based on several diagnostic parameters. To each one of these parameters is assigned a weighing factor, depending

on the importance of this diagnostic parameter for the characterization of the condition of this transformer component (for example the tap changer, or any other component).

On the other hand, depending on the value of each parameter, it is also assigned a score (for example 0, 1, 2, 3 or 4) to this parameter.

The sum of the individual "weighed" scores (score multiplied by its "weighing" factor), calculated for each parameter is the "Health Index" of this transformer component.

*Step 4. - Calculate the global "Health Index" for each transformer.*

The global "Health Index" of a transformer (HI) is calculated by the weighed sum of the "Health Index" of each one of the most important transformer components, from which there are information available.

The results of the calculations must be "normalized", in order to make the final result meaningful.

This is a general procedure for calculation that can be adapted to each particular case. For example, instead of considering all the sub-systems, separately, we can include all of them in the same term of the sum and only consider separately the tap-changer, which is the element of the transformer about which it is more common to have specific information.

In this case, we have a simplified sum, with only 2 terms, as referred by Gorgan et al [3] and A. Naderian et al [4-5] to determine the global "Health Index" (HI) of the transformer, where X = 60% and Y = 40% .

$$\text{HI} = X\% \; \frac{\sum_{j=1}^{n} K_j \, s_j}{\sum_{j=1}^{n} 4 \, K_j} \; + \; Y\% \; \frac{\sum_{j=n+1}^{z} K_j \, S_j}{\sum_{j=n+1}^{z} 4 \, K_j} \quad (1)$$

Where:

$S_j$ – Score corresponding to parameter "j"

$K_j$ – "Weighing factor" corresponding to parameter "j"

j – Number of each diagnostic parameter, used for calculation of the "Health Index"

with   X(%)+Y(%) = 100 (%)

In formula 1, the first term is the contribution of the "Health Index" calculated for all components of the transformer, excluding the tap-changer, for the global "Health Index" of the transformer (HI), and the second term is the contribution of the "Health Index" of the tap-changer, also for the global "Health Index" of the transformer (HI).

X and Y are the weighing factors (in %) of these 2 indexes, for the calculation of the transformer global "Health Index".

According to the last CIGRÉ survey [14], Y (% of failures due to problems in on-load tap-changers), is 26% for transformers of Substations (in this case X will be 74%), while Y is 11% for transformers of Power Stations (and so in this case X = 89%).

Concerning the "physical health parameters", they are based on visual inspection, or derived from the number of corrective maintenance work orders.

It is important to highlight, that the diagnostic parameters used for the calculation of the "Health Index" depend mainly on the availability of information about those parameters, for the transformers to be evaluated. Also the importance assigned to each parameter (expressed by the "weighing factor" attributed to each parameter) depends on the evaluation of the experts.

It also must be underlined here, that the calculation of a "Health Index" is based on the knowledge of an interdisciplinary group of experts, responsible not only for the interpretation of the results of each test, and for their conversion in scores, but also for the interpretation of the data coming from inspections and maintenance work, besides the historical data.

The "limit"/"boundary" values, which are the frontiers for different conditions of equipment (corresponding to different "scores"), depending on the case, can be based on standards (like for example IEC 60422 [15] and IEC 60599, [12]), based on statistical studies for a meaningful population of transformers, or, in some cases, can come from the specific experts knowledge.

In case all the parameters of table 1 are used to calculate the "Health Index" using formula (1), we should replace in this formula "n" and "z", by:

n = 16 and z = 19

since the last 3 parameters listed in this table are only related on the condition of the tap-changer.

In the next Sub-clause (4.2) is exemplified how to assign a score to a parameter, in order to be possible to apply Formula 1 to calculate the global "Health Index" of a transformer.

Table 1. Example of "Health Index" diagnostic parameters scoring and weighting factors ($K_j$) assigned to each parameter

| # | Transformer Condition Parameter | $K_j$ | $S_j$ |
|---|---|---|---|
| 1 | DGA | 10 | 4, 3, 2, 1, 0 |
| 2 | Load history | 10 | " |
| 3 | Dissipation Factor of the transf. | 10 | " |
| 4 | Infrared Thermography | 8 | " |
| 5 | Oil Quality | 8 | " |
| 6 | Furanic Compounds Content | 9 | " |
| 7 | Age | 4 | " |
| 8 | Leakage Reactance | 8 | " |
| 9 | Winding Resistance | 8 | " |
| 10 | FRA | 6 | " |
| 11 | Core-to-ground Connection | 2 | " |
| 12 | Preservation System Condition | 1 | " |
| 13 | Main Tank Corrosion | 1 | " |
| 14 | Cooling Equipment Condition | 3 | " |
| 15 | Bushings Condition | 7 | " |
| 16 | Oil Leaks | 2 | " |
| 17 | DGA of Tap-changer oil | 6 | " |
| 18 | Tap-changer Oil Quality | 3 | " |
| 19 | Tap-changer Contacts Condition | 5 | " |

### 4.2 Example of how to assign a score to a parameter

Considering for example a transformer which oil has a 2FAL content of 0.4 mg/kg, using Table 2, we can assign the score 3 to this parameter.

As the other furanic compounds can be found in the oil, only very seldom, we only considered 2FAL in this parameter).

Table 2. Furanic compounds (2FAL) – Scores

| Score | 2 FAL (mg/kg) |
|---|---|
| 4 | 2 FAL ≤ 0,30 |
| 3 | 0.30 < 2 FAL ≤ 0.50 |
| 2 | 0.50 < 2 FAL ≤ 1.00 |
| 1 | 1.00 < 2 FAL ≤ 3.00 |
| 0 | 2 FAL > 3.00 |

According to Table 1, the weight of this parameter is 9, what means that the contribution of this parameter to the calculation is 27.

The values of Table 2 are a bit different from the values presented by other authors, [5] since they were calculated for the Portuguese population of transformers filled with uninhibited oils.

For another parameter, for example the transformer dissipation factor (Tgδ), if the transformer to be assessed has for example, a Tgδ = 0.8 the corresponding score is 2, according to Table 3, so the contribution of this parameter for the HI calculation will be the product of 2 by 10 (since 10 is the weighing factor of Tgδ, according to Table 1).

Table 3. Dissipation factor (Tgδ) – Scores [5]

| Score | Dissipation Factor (%) |
|---|---|
| 4 | Tgδ < 0.5 |
| 3 | 0.5 ≤ Tgδ < 0.7 |
| 2 | 0.7 ≤ Tgδ < 1.0 |
| 1 | 1.0 ≤ Tgδ < 2.0 |
| 0 | Tgδ ≥ 2.0 |

The same procedure is applicable to all the other parameters.
Applying formula 1, we can obtain the global HI of the transformer, which will be a value in the range 0% to 100%.

So, the fleet of transformers can be ranked by their HI, and depending on the value of HI it is possible to give some guidance to the asset manager, concerning the most suitable actions to be taken, regarding each transformer. These recommendations are summarized in Table 4.

Table 4. Health index scale [5]

| HI (%) | Condition | Actions |
|---|---|---|
| 85-100 | very good | normal maintenance |
| 70-85 | good | normal maintenance |
| 50-70 | fair | increase the number of diagnostic tests, corrective maintenance or need of replacement, depending on the criticity |
| 30-50 | poor | start planning the replacement process or repair, taking in account the risk |
| 0-30 | very poor | immediate risk assessment, replacement or repair, depending on the case |

This method has been applied to some fleets of transformers owned by some Companies of EDP Group and has given consistent results.

Recently, we have introduced some improvements in this method, to take in account for example the problems related on the presence of corrosive sulphur in oil and the consequent countermeasure used to solve the problem, by addition of a passivator to the oil.

From our point of view, this problem which has not been addressed in the calculation of the "Health Index", should be taken in account.

In Table 5 we summarize our scores, used for this parameter.

Table 5. Oil corrosivity – Scores

| Score | Corrosive and Potentially corrosive Sulphur tests[1] |
|-------|------------------------------------------------------|
| 1 | Non corrosive unpassivated oil – negative values in both corrosive sulphur tests [1] |
| 2 | Negative result in both corrosive sulphur tests, but [Passivator] in oil higher than 60mg/kg |
| 3 | Negative result in both corrosive sulphur tests, but [Passivator] in oil between 60mg/kg and 20mg/kg |
| 4 | Positive result in at least 1 corrosive sulphur test, or negative results in both tests for oils with [Passivator]< 20mg/kg |

(1)Tests according to IEC 62535 [16] and DIN 51353, [17]

This parameter to which we attributed a weighing factor of 8 is included in our "Oil quality" parameter.
Besides this test, we have included in the "Oil quality" parameter, several other tests, like for example the electrical breakdown, the interfacial tension, the moisture content, the acidity and the color, each one with its weighing factor and its "Table of Scores".
In case of the above-mentioned tests included in the "Oil quality" parameter, the limit values that we have used for the assignment of codes are based on the IEC 60422 [15], and also on our own experience.

However, besides the important information extracted from the "Health index", as all transformers do not have the same importance in the network, the problems associated to the replacement of a failed transformer can be very different, depending on several factors. To take these factors in account, a "Criticality Index" was created, [8, 9,11].

## 5. Criticality Index

The "Criticality Index" is an index created to take in account the relative importance of an event, like a failure of a transformer, in different situations, that make the replacement of a failed transformer easier, or more difficult, depending, for example, on the availability of a spare transformer to replace the failed one, the difficulty to move the transformer due to its dimension, the difficulty of the repair due to problematic accessibility, or the unavailability of pieces to make the repair.
Moreover, not all the transformers have the same importance for the electrical system, because this depends, for instance, on the transformer location, in what concerns, to public or workers safety, its type (for example GSU, transmission, distribution), and other parameters.
The "Criticality Index" tries to mirror the strategic importance of a transformer, in a network. So, combining the "Health Index" and the "Criticality Index" and depicting both indexes in a graph, it is easier to identify the transformers which are OK and so can continue having their normal maintenance programme and also the units that need an immediate further testing and/or inspection, in order to decide about the most suitable corrective actions, that should be taken (transformers with the lowest "Health Index").
The transformers that have the lowest "Health Index" and the highest "Criticality Index", will have the highest priority to be refurbished or to be replaced, depending on the cases.
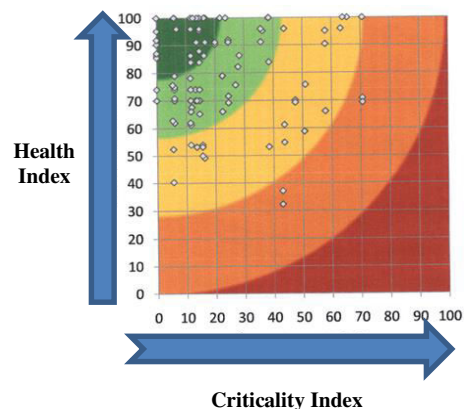


Fig. 1. Condition of a fleet of transformers. Each small circle represents a transformer.

So, the combination in a 2 axis graph, of the "Health Index" with the "Criticality Index", usually gives a valuable information to the asset manager. The application of a colour code to this graph, makes its use, easier.

For example, the good transformers are located in a green sector, while the red sector contains the equipments that require urgent actions.

So, by using this type of graph, the asset manager can quickly know, to which transformers, he must draw his attention, firstly.

## 6. Conclusion

Condition and risk assessment are more and more important for asset managers.

Using the "Health Index", the condition of a power transformer can be assessed. The "Health Index" gives information about the suitability of an asset for continued service, containing objective information that can be easily checked.

The calculation of a "Health Index" is based on specific diagnostic parameters, to which one is assigned a score and a weighing factor. Afterwards, all the weighed scores are combined to calculate the global "Health Index" of the transformer.

By developing a condition assessment of their equipments, based on "Health Index", the utilities increase their ability to operate their networks, not only optimizing the use of existing equipment, but also planning the maintenance actions, repairs, refurbishments, relocation or replacement, in the best way.

The calculation of a "Health Index" is based on the information about aging and degradation modes of the transformers and their sub-systems, under different operating conditions. [9]

The "Health Index" is used to measure and monitor the condition of the assets and combined with the "Criticality Index", became a powerful tool in asset management, crucial for the identification of investment needs and for prioritizing investments in capital and maintenance programs. [10]

The "Health Index" helps the asset managers, not only in what concerns to the identification of the transformers in worst technical condition, for possible replacement, but also helps to select equipments that need special maintenance actions, or a more frequent supervision tests, in order to better understand and characterize their suspicious condition and consequently better define the most suitable maintenance methods, to improve their condition and extend their useful life.

It is important to highlight that the "Health Indexes" of a fleet of transformers provide a picture of the condition of this fleet, at a certain moment, so these "Health Indexes" have to be updated, with a frequency that depends on several factors, including the main needs and the criteria of the asset manager.

Finally, other concepts like the "Ageing Index" presented recently by Y. Liu and al. [18] are quite similar to the Health Index".

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