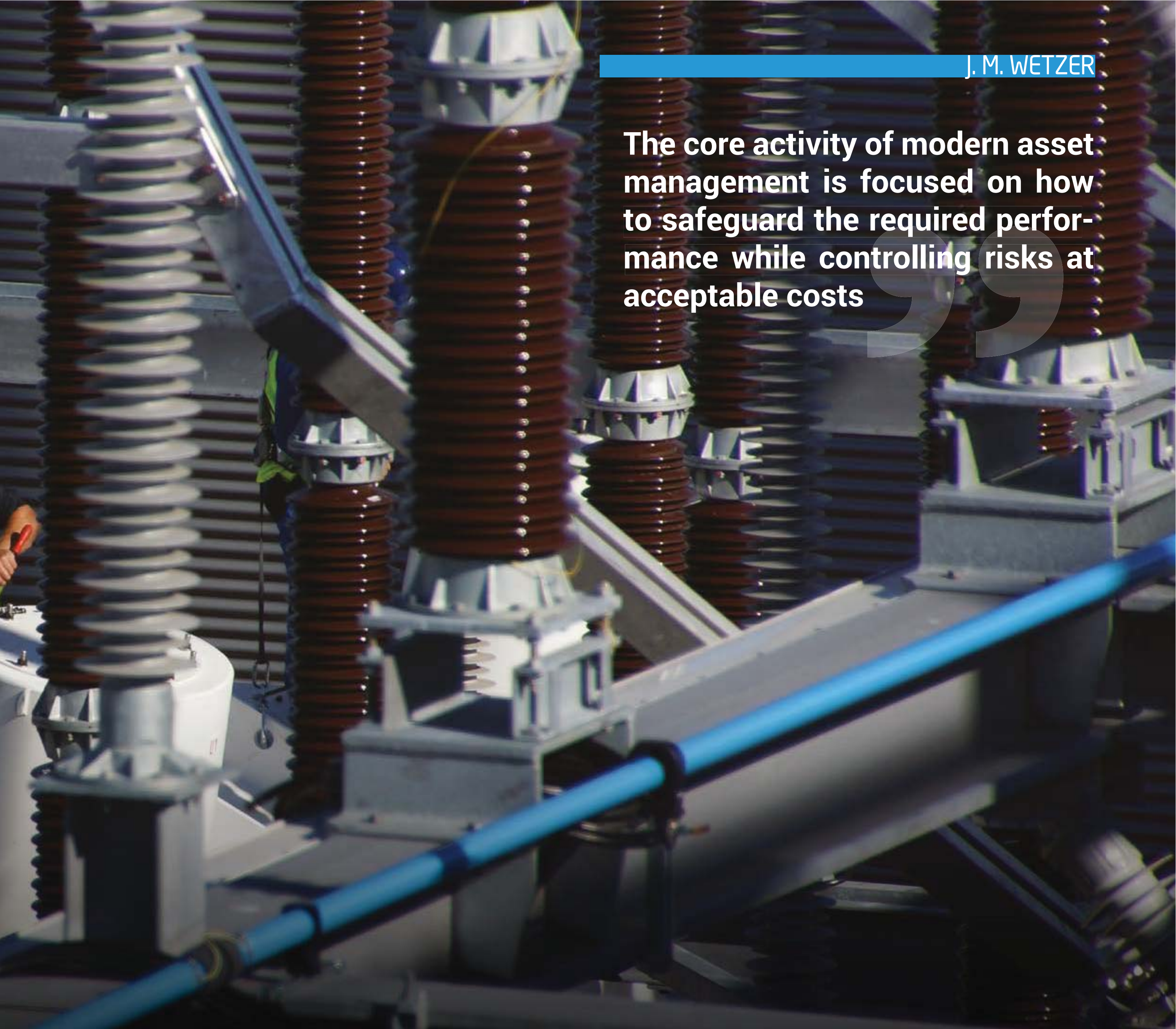
Transformer measurement policies for optimum asset management value

J. M. WETZER



The core activity of modern asset management is focused on how to safeguard the required performance while controlling risks at acceptable costs

Summary

Power transformers are crucial components in networks for the transmission and distribution of electrical power. For the network manager, the health of the transformer fleet is of high importance in order to ensure a reliable grid. It requires appropriate maintenance processes and replacement decisions to safeguard that reliability. For monitoring the health, or condition, of transformers, an abundance of measurement options is at the disposal of the asset manager. In this column, we will address how an asset manager can best use these options to his benefit.

Firstly, this contribution discusses the interaction between asset management and measurements. Secondly, we will present what diagnostic options and measurement policies are at the disposal of the asset manager, and discuss a number of relevant choices to be made and aspects to be taken into account.

1. Introduction

Power transformers are crucial components in our systems for transmission and distribution of electrical power. They allow electrical power to be transported at any voltage level, thereby keeping losses limited and networks more stable. For the network manager, the health of the transformer fleet is, first of all, needed to ensure a reliable grid. Secondly, he has to ensure other values such as safety and cost efficiency. For that purpose, the asset manager needs to monitor the condition of the transformers, organize appropriate maintenance, and decide on timely replacement.

The asset manager has an abundance of measurement options at his disposal for condition monitoring. One of the challenges the asset manager faces is the development of an adequate set of techniques from a large variety of available options. Another challenge is how to integrate condition assessment in the asset management process in a smart way: how to optimize maintenance processes and replacement decisions, thereby optimally assuring reliability and control over risks and costs. The measuring policy however, will not only depend on the available options, but also on the expected costs and benefits of using condition assessment, and the effectiveness of mitigating risks.

Firstly, we will discuss the interaction between asset management and measurements. On the one hand, the results of measurements directly influence asset

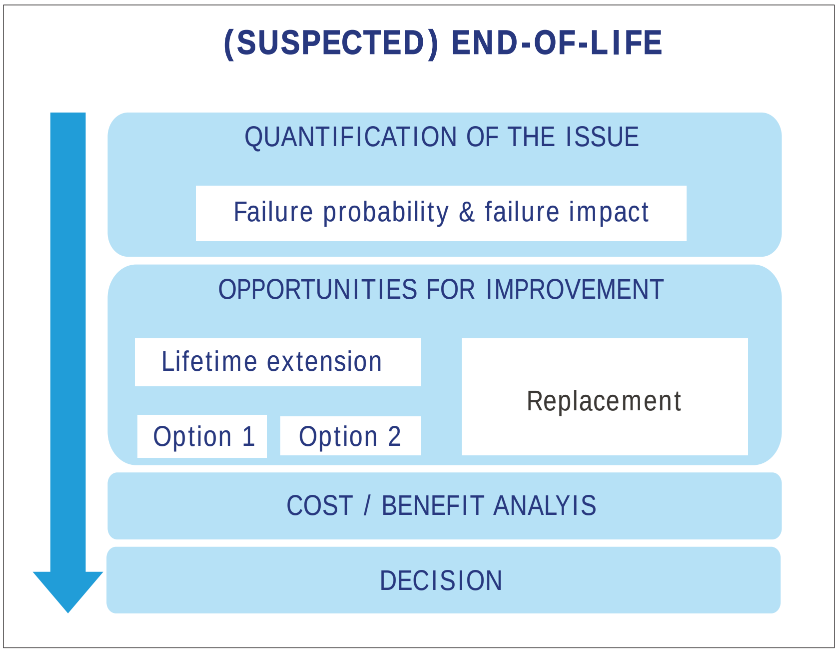


Figure 1. Example of a decision diagram of an (suspected) end-of-life issue

management decisions, and on the other, the asset manager has to decide which measuring policies to adopt. Secondly, we will present what kind of diagnostic options and measurement policies are at the disposal of the asset manager, and discuss a number of relevant choices to be made and aspects to be taken into account.

2. Asset management

2.1 Asset management background

The core activity of modern asset management is focused on how to safeguard the required performance while controlling risks (against various business values) at acceptable costs. Asset management involves the complete asset lifecycle [1]. In this column, we focus on the operational life of the transformer. In this lifecycle phase, asset management decisions are often related to the condition of the assets. Some examples are:

- Aging and maintenance (condition-based maintenance, indicators, intervals)
- Aging and end-of-life (lifetime extension, replacement, refurbishment, maintenance)
- Upgrading and uprating assets

2.2 Asset management decision making

Network management is increasingly governed by a risk based decision making process, based on modern asset management standards such as ISO 55001 [2]. As elaborated in [1], such asset management decisions follow these steps:

- Assess the risk by evaluating the probability and the impact of failure
- Use a risk framework (e.g. a risk matrix) and the company's risk appetite to establish the urgency
- Evaluate the mitigating options, compare the expected results, and create the portfolio
- Prioritize and manage the portfolio.

Measurements and condition assessment are reflected in two ways. On the one hand, condition assessment is relevant as input for the decision making process, in particular while establishing the probability of failure. This is reflected in Figure 1, which shows a decision diagram of an (suspected) end-of-life issue.

In this decision scheme, the major role of the condition assessment is to estimate the probability of failure and, to some extent, the effectiveness of mitigating measures. This decision scheme may be extended to incorporate the full evaluation of the impact of failure, thus providing the required decision information on the risk, urgency, and priority of immanent failure with regard to the business values at hand (reliability,

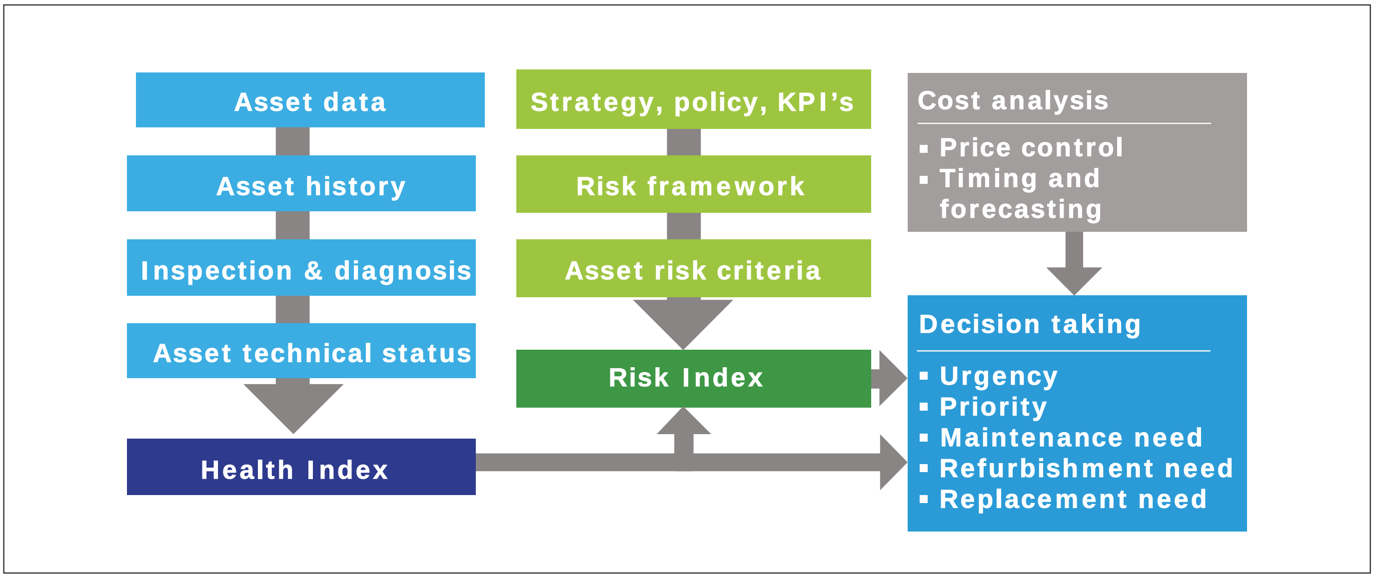


Figure 2. Example of a risk-based decision diagram

safety, cost, compliance and so on). This is illustrated in the decision diagram shown in Figure 2 [3].

On the other hand, deciding what measurements and condition assessment techniques to apply is also a risk-based asset management decision. The measuring policy will not only be dependent on the available options, but also on the expected costs and benefits of using condition assessment. High voltage transformers are few in number, are relatively expensive and have a high impact upon failure. As a result, they will allow higher investments in monitoring and still deliver a positive cost/benefit ratio. Low and medium voltage transformers, on the other hand, are huge in number, less expensive, and have a relatively low impact upon failure. Here a positive cost/benefit ratio is harder to achieve.

In the remainder of this column we will focus on diagnostic options and features, bearing in mind that the choice of what options to apply is governed by the above decision making processes.

3. Diagnostic options

When applying measuring techniques for condition assessment, one of the main issues is the choice of an adequate set of techniques from the abundance of available options. There is a variety of on-line and off-line techniques, built-in and external sensors, interpretation models and algorithms, and complete diagnostic systems, stand-alone or connected to computers by means of communication systems. For any specific individual type of defect, many sources give guidance as to what would be an adequate technique for that specific type of defect (see for example [4, 5, 6]). However, when it comes to developing a sufficient and adequate set of techniques to cover the transformer as a whole, be it for a single distribution or transmission transformer, or for a fleet of transformers, the following key questions need to be answered first:
- What are the dominant failure modes that the transformer needs to be protected against
- What are the indicators describing the defect status and urgency for each failure mode
- What measuring options are available (or needed) to assess the defect status and urgency
- For each measuring option:
  - what are the knowledge rules or systems to assess defect status and urgency;
  - what is the probability the cost, and the benefit of detection;

A well-structured approach to this is the Failure Mode Effect (and Criticality) Analysis or FME(C)A [7]. This methodology also forms the core of structured processes for the development of maintenance processes such as Reliability Centred Maintenance (RCM) [7, 8].

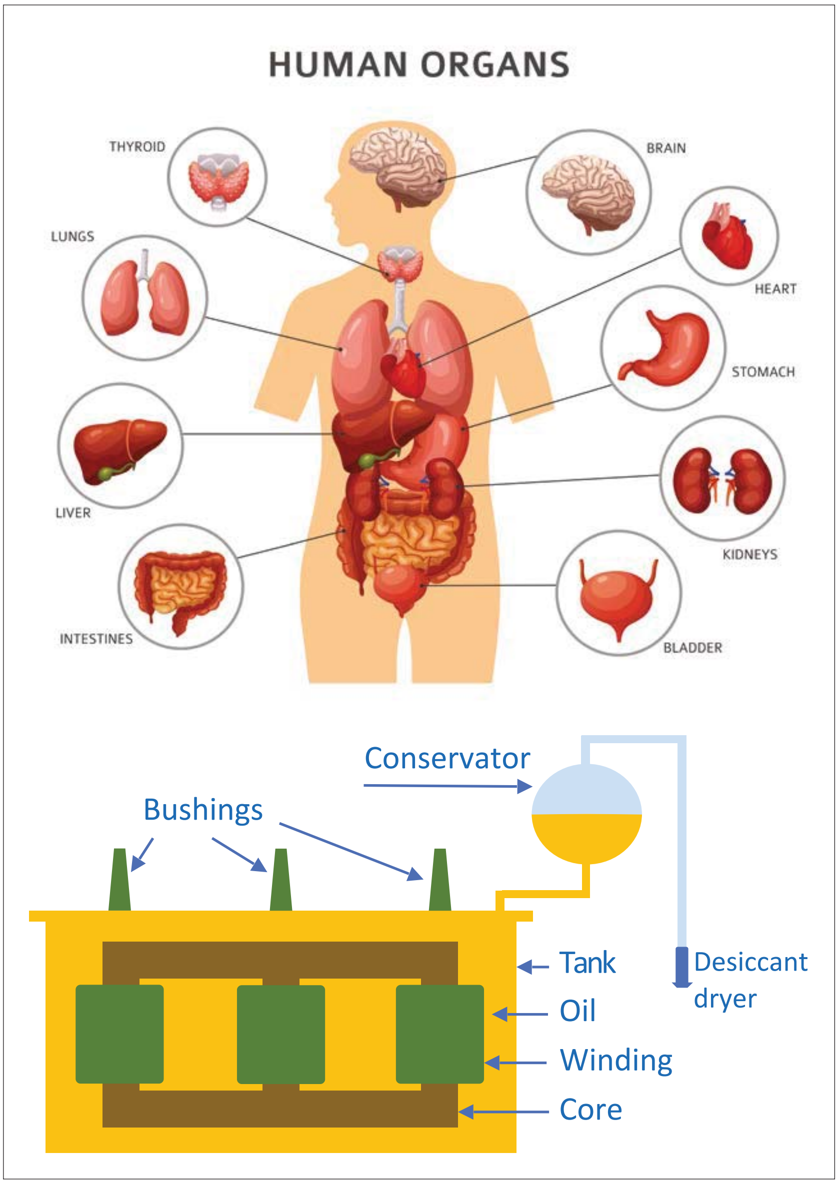


Figure 3. Diagnosis Analogy: human being versus transformer

The purpose of a measurement is to identify signs of degradation or impending failure, using appropriate indicators, what is commonly called condition assessment

4. Measurement policies

4.1 Funnel or sieve approach

When diagnosing the condition or health of a transformer, it is not efficient or affordable to simply apply all known or available techniques. We may compare this with diagnosing a human being with health complaints (Figure 3).

Table 1. A human analogy of transformer diagnosis

Transformer	Human analogy	Activity
History and symptoms (maintenance engineer)	Anamnesis and complaints (general practitioner)	Collecting facts Narrow down by elimination
Oil (DGA) analysis (laboratory)	Blood / urine analysis (laboratory)	Indication of defects Guidance for further analysis
Routine measurements (technician)	Routine tests (general practitioner)	Defect analysis Need for treatment / maintenance
Advanced measurements (transformer engineer)	Advanced tests (medical specialist)	Advanced diagnosis Need for refurbishment / replacement
Repair (workshop / factory)	Surgery (surgeon)	Repair, refurbishment, replacement of subcomponents
Post-mortem analysis (transformer specialist)	Post-mortem analysis (medical examiner)	Establish cause of failure / death Lessons learned

When applying measuring techniques for condition assessment, one of the main issues is the choice of an adequate set of techniques from the abundance of available options

Table 1 further illustrates the steps in a condition assessment approach. In the medical analogy, a general practitioner will first try to understand the nature and the history of the complaints. Next, some indicative tests may be performed (such as blood or urine analysis), as well as some routine tests (e.g. reflexes and blood pressure). If this does not lead to a diagnosis, the patient will be referred to a specialist who may do some advanced diagnostic tests (MRI, X-ray and the like) and finally decide whether to perform surgery, administer drugs, perform dialysis, recommend a change of an unhealthy lifestyle, and so on.

Likewise, for transformers, after looking at the transformer history and issues, the first step is to perform oil analysis. It was discussed earlier that the transformer oil analysis (including dissolved gas analysis or DGA) is a very powerful diagnostic tool [9]. Next steps may include routine or advanced diagnostic techniques and internal inspections.

Such a stepwise approach is called a funnel or sieve approach: each step narrows down the required options for the next step. This approach may be applied as part of a condition-based

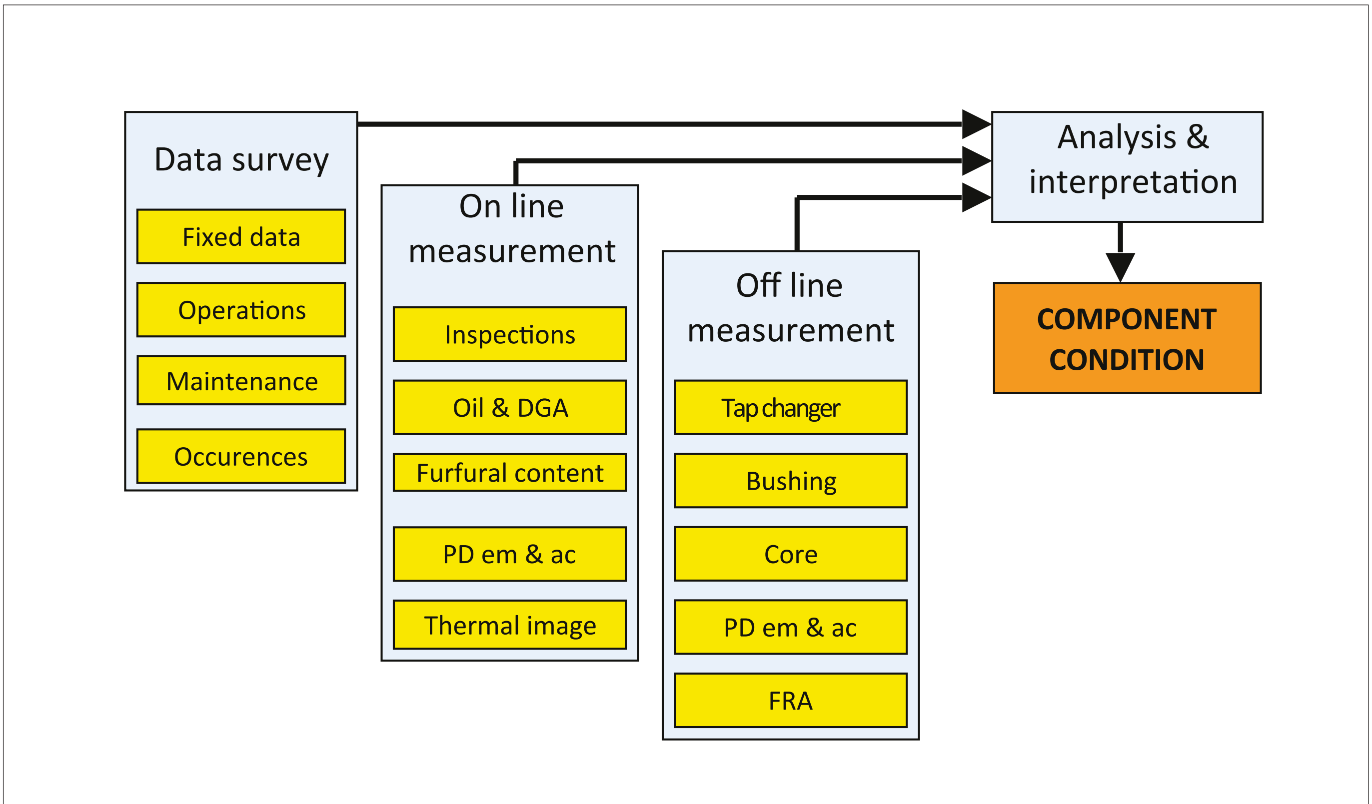


Figure 4. Example of a funnel diagnostic scheme

The measuring policy does not only depend on the available options, but also on the expected costs and benefits of using condition assessment and on the effectiveness of mitigating risks

maintenance program, or for assessing the health of a transformer population. An example of a funnel scheme is shown in Figure 4.

4.2 Diagnostic classification

Depending on the question at hand, the funnel approach leads to stratified categories of diagnostic techniques [6]:

- **Oil analysis**. Transformer oil contains a wealth of condition indicators, not only for the thermal and dielectric oil quality, but also for all kinds of transformer defects. Oil analysis is THE basis for transformer condition assessment.
- **Quick scan techniques**. A quick scan is a fast procedure during which equipment does not have to be shut down, and that provides a first indication of possible defects. A quick scan may involve visual inspections, infrared (IR) thermography (for thermal defects) and routine partial discharge detection (for dielectric defects). Together with oil analysis, quick scan techniques are able to detect a large number of defects in the early stage of development.
- **Routine measurements**. Routine measurements are relatively simple standard measurements. They are often performed on a regular basis as a part of a maintenance program or they may be triggered by another event (for example by a Buchholz trip). Examples include measurement of the turns ratio, conductor resistance, capacitance or loss angle (or power factor), insulation resistance, and earthing tests. Usually the transformer needs to be taken out of operation.
- **Advanced measurements**. Advanced measurements are more complex measurements that are performed by specialized staff. They are usually triggered by an event or by the need for a revision, lifetime extension, or prolonged operation. However, they may also be part of a condition-based maintenance scheme. Examples include Frequency Response Analysis or FRA, Frequency Domain Spectroscopy or FDS, tap changer diagnosis, and lifetime estimation. The transformer needs to be taken out of operation when performing these measurements.
- **Post-mortem analysis**. As the name says, post-mortem analysis is performed after a transformer has failed or is taken out of operation. In most cases, the purpose of this analysis is to understand the root cause of failure, usually to decide on measures that reduce the probability of recurrence, sometimes for insurance purposes. Another reason for the analysis may be to confront measuring results and actual degradation for improving knowledge rules.

4.3 Condition classification

Formally, a transformer measurement can be defined as capturing the value of a transformer property. When performing measurements to establish the maintenance or replacement need, the purpose of a measurement is to identify signs of degradation or impending failure, using appropriate indicators. This is commonly called condition assessment.

The primary purpose of condition assessment is to identify the type and degree of the degradation or defect. Schematically, condition is often depicted as a gradually declining function going through the phases such as: as good as new – normal degradation – defective – faulty – failed [13], as shown in Figure 5.

The different phases may be characterized as:

1. as good as new – cannot be distinguished from new

A funnel or sieve approach, with a stratification of diagnostic techniques, allows an effective and efficient condition assessment for maintenance applications and population screening

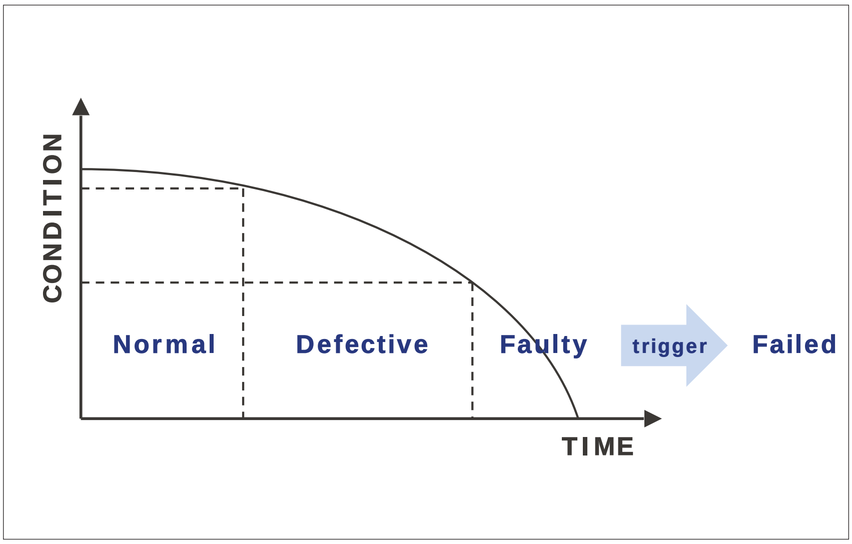


Figure 5. Schematic development of equipment condition in time

Class	Status	Action
1	No defect	No action
2	Possible defects / early stage defect	Repeat after time or further diagnosis
3	Probable defect	Further diagnosis, assess severity[1]
4	Certain, non-critical[1], defect	Plan repair
5	Certain, critical[1], defect	Immediate repair

1) Severity and criticality dependent on risk (failure probability x failure impact)

Figure 6. Example of condition classification

Statistical screening techniques may be employed for policy development and budget assignment, but not for the decisions involving maintenance and replacement

2. normal degradation – functionality is not influenced
3. defective – functionality is influenced but still meets requirements
4. faulty – no longer meets minimum requirements
5. failed – trigger has caused equipment to fail

When performing measurements for the purpose of assessing the condition, it is recommendable to not only assess the type and degree of degradation or defect, but also the urgency and the required action. An example of such a classified condition assessment is shown in Figure 6.

4.4 Population screening

The approach for assessing the condition of a transformer population depends on the goal of the assessment. If the goal is to identify the transformers that need attention (additional maintenance, revision, replacement) again, a funnel approach can be applied, similar to

Figure 4. As an example, one can use the following approach:

- Firstly, the known history of the whole population is analysed, including the most recent oil analysis, maintenance records and failure events;
- Next, the whole population is subjected to a visual inspection, possibly combined with one or more quick scan techniques; if needed, new oil samples are taken for analysis;
- For those transformers that are identified as possibly suspect, a choice of additional routine measurements may be performed;
- For those transformers that are still identified as suspect, some additional advanced measurements are executed.

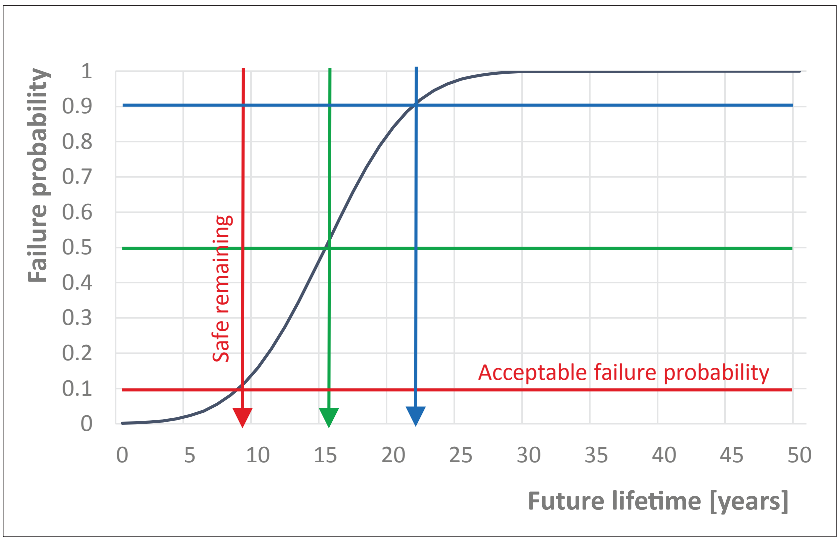


Figure 7. (Safe) remaining life from failure probability versus time

It is not possible to forecast when an individual transformer will fail, but we can forecast how the failure probability develops over time. The "safe" remaining life depends on the risk appetite of the asset manager

If the purpose of the population study is not to identify suspect transformers but to establish how many transformers are suspect, need replacement, repair or revision, statistical techniques can be employed. This is similar to a population health screening, and can serve to develop policies or assign budgets. In that case, the population is divided into subpopulations with similar characteristics (same voltage, power, type), and then from each subpopulation a representative sample is selected, and the sample is subjected to a condition assessment (for example using a funnel approach). The results are then "translated" back to the full population in order to arrive at statistical conclusion (expectation, spread, confidence level).

4.5 Lifetime estimation

Lifetime estimation is a term that is often misused. It suggests that the end-of-life can be predicted, in other words: that we can predict when a transformer will fail. In practice, the best we can do is forecast how the failure probability evolves in time. This is based on (a series of) measured condition parameters on the one hand, and on an understanding of the degradation process and its evolution in time on the other. Since the condition parameters correspond to a certain failure probability, we may eventually derive a prediction of the failure probability versus time. What we then call the end-of-life depends on the failure probability that the asset manager is willing to accept. In other words: end-of-life is a risk based decision. This is illustrated in Figure 7.

The end-of-life of a transformer is usually associated with the mechanism of winding paper degradation. The reason for this is not that this is the most frequent failure mechanism, but because it is the only irreversible mechanism (from a practical point of view).

There are basically two types of methods for estimating the remaining life. One is based on a thermal model, the loading guide, which estimates the loss of life dependent on the load history and the ambient temperature history [10, 11]. A more sophisticated approach for single transformers and populations is presented in [12].

Another method is by measuring paper degradation by-products in the oil. The most common by-product used in the analysis is a furfural compound called 2-furaldehyde (or 2FAL). The concentration of 2FAL in the oil is a measure of the degree of polymerization (DP) of the winding paper. Recently, methanol has been identified as a possible alternative for 2-furaldehyde [9].

In a next column we will present a more thorough description of the methods for remaining life estimation.

5. Continuous monitoring

Recently, there has been a growing attention concerning continuous on-line monitoring. The advantages seem attractive: there is no need to visit substations and connect measuring equipment, communication facilities and web-based applications are readily available, we don't need to worry about measuring intervals and defects can be immediately detected, we have a real-time insight into the condition of our fleet. However, there are some drawbacks and pitfalls that justify caution:

- Not all condition parameters can be monitored. Therefore, visiting substations will remain necessary if only for visual inspections, maintenance, signs of leakages, safety, burglary and theft;
- Monitoring systems are usually less reliable than power equipment and

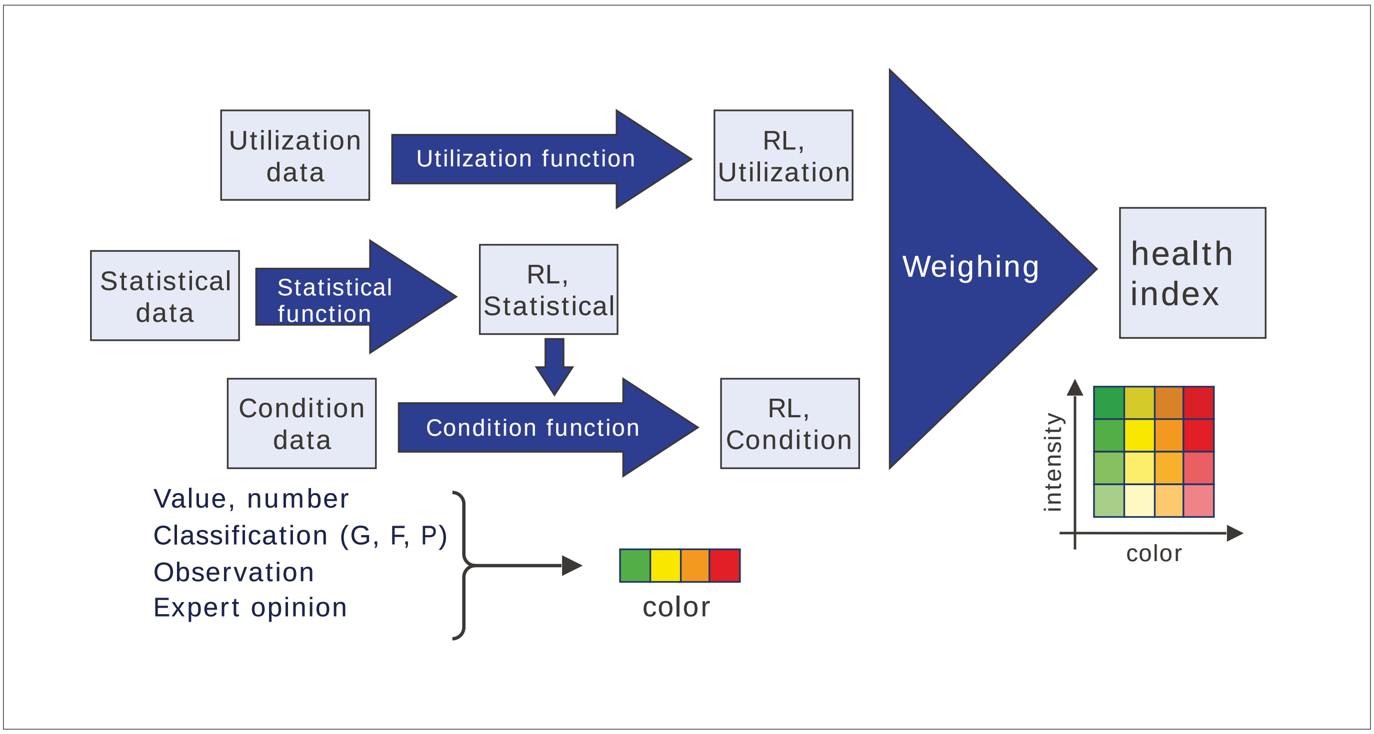


Figure 8. Example of a health indexing scheme [3]

have a shorter lifespan; they have to be checked, calibrated, maintained, repaired and replaced;

- For many commodities such as medium voltage transformers, on-line monitoring offers insufficient advantages for a positive cost / benefit analysis;
- Condition monitoring requires massive data flows to be managed, stored and analysed.

Presently, continuous monitoring is predominantly applied to selected high voltage transformers, in particular, transformers that are hard to access, have a strategic function, or lack redundancy.
For more information we refer to the relevant CIGRÉ Technical brochures [4, 5, 13].

6. Managing diagnostic data

In order to manage large amounts of transformer condition data, and turn it into information that supports the asset manager in taking well-substantiated decisions, health indexing methods are used. A health index is used to represent the condition or health of an asset. In an earlier column [3], we discussed the requirements a health index system needs to display for it to be beneficial for decision making, among which are

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the availability of suitable condition indicators, the use of operational and statistical data next to condition data, the data quality issues and the associated confidence level, and the ways to aggregate data to the transformer level, and making it actionable and fit for decision making. Figure 8 and 9 show some examples of a health indexing scheme and approach [3].

For more detailed description of health indexing one can also refer to the recently published CIGRÉ Technical Brochure on Transformer Condition Assessment [14].

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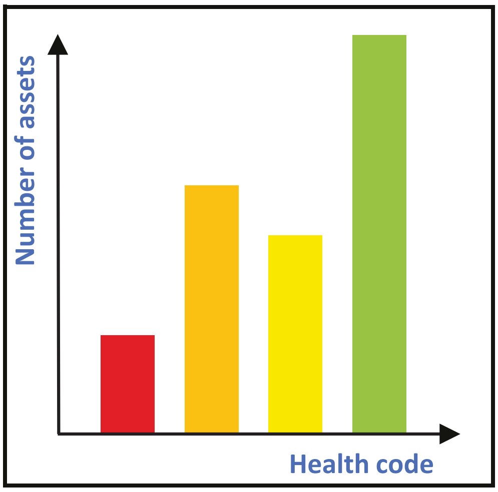

Figure 9a

Impact / Rem. lifetime	Negligable	Small	Moderate	Severe	Catastrophic
< 2 years	0	1	3	0	0
2-4 years	0	2	2	0	1
4-8 years	1	0	7	8	2
8-15 years	8	14	5	4	6
> 15 years	17	29	38	0	1

Figure 9b

Figure 9a and 9b. Examples of a health and risk approach indexing results [3] Left: health histogram – Right: risk matrix

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Author

Dr. Jos Wetzer from the Netherlands is senior principal consultant "Asset Management" with DNV GL - Energy, stationed in Arnhem, The Netherlands. He obtained a M.Sc. degree in Electrical Engineering (cum laude) and a Ph.D. degree in Technical Sciences, both from the Eindhoven University of Technology. After obtaining his Ph.D. degree he worked as an associate professor at the Eindhoven University of Technology for 14 years. His activities included research, education and consultancy in the field of High-Voltage Engineering and EMC. In 1998 he joined KEMA (now DNV GL) as a senior consultant, in the field of condition assessment, asset management and EMC. From 2001 to 2006 he held a management position, and from 2006 on he has been active as a (senior) principal consultant, and has served numerous clients in Europe, North America, the Middle East and Asia Pacific on asset management issues. From 2004 to 2007 he also held a position as a part-time professor at the Eindhoven University of Technology in the Netherlands, engaged in Asset Management of Electrical Infrastructures. His expertise includes asset and maintenance management, condition assessment and diagnostics, dielectrics and electrical insulation, electromagnetic fields and EMC. He has published over 150 scientific and professional publications.