Condition-based evaluation

A new platform for power equipment life management

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Condition-based evaluation helps electric utilities decide if and when installed power equipment, such as a power transformer, needs to be repaired, replaced or upgraded to maximize operation and profit. To determine the individual equipment risks and capabilities associated with different power system scenarios, it relies on objective information that can vary from 'crisp' numerical data to vague details expressed in 'natural language'. Utilities can use this method to improve equipment availability and reliability, reduce lifetime costs, and make maintenance and replacement scheduling more efficient.

1 Power equipment, such as this power transformer, is a valuable asset. When a utility decides to repair, replace or refurbish it is therefore an important decision.

Deregulation of the energy market is bringing about a fundamental change in the way power equipment assets have to be operated, maintained and replaced. High power-equipment performance is key to cost-efficient energy trading and to the success of the efforts being made by utilities to satisfy end-user demand for high power quality 1.

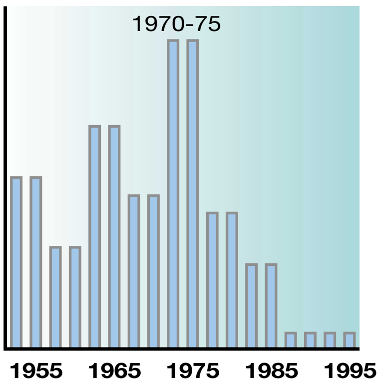
Three main trends are shaping power equipment life management today:

- Prolongation of the equipment's operational life
- Tolerance of equipment being operated closer to its limits
- Cost-effective and adaptive replacement and maintenance strategies

These trends are, at least in part, contradictory. Downsizing maintenance crews and effort, reducing repair activities and delaying replacement can lead to power equipment malfunctioning and unexpected and costly system outages. In countries where the installed power assets are old and a large proportion of the equipment is approaching the end of its expected lifetime 2, such a strategy can have serious consequences.

Replacement or some kind of refurbishment could soon become necessary for a lot of the older installed units.

2 Power transformer units installed in western countries in recent decades. Typical profile, illustrating an aging population



However, replacing all of them within a short period of time is likely to be as much of a problem and a burden to the manufacturers as it is to the users.

A new strategy for equipment replacement and refurbishment is therefore needed. This should aim at identifying the most vulnerable, and therefore most critical, pieces of equipment, which would then be dealt with first. To be successful and efficient, such an approach has to be based on a condition-based assessment of the equipment.

Towards more objective life management

Life management of power equipment involves a chain of decisions, made over the equipment's service life and aimed at safe, reliable and cost-effective power system operation.

There are three important tasks that life management needs to address. The first of these is *incipient failure detection* and the avoidance of unexpected equipment failures; the second is the *identification of equipment malfunction* or faulty states; and the third is *strategic planning* of the power assets. Since strategic planning includes among its goals efficient operation and maintenance scheduling, it has to give consideration to the replacement and repair and maintenance activities that are necessary to ensure high availability

Three basic techniques have been developed to perform these tasks *(Table 1)*:

- Equipment monitoring
- Equipment diagnosis
- Condition-based evaluation and life assessment

Traditionally, equipment replacement decisions have been based on just the equipment age or on subjective criteria. As this is obviously unsatisfactory, various alternative methods have been tried out over the years.

Evolution of equipment evaluation methods

Two main groups of equipment evaluation methods have evolved: *statistical methods* and *individual oriented approaches.*

For the *statistical methods*, statistically relevant data are needed. These must be reliable and available in sufficiently large quantities. In addition, the equipment units should preferably have only one simple and well-understood failure mechanism and be of similar design. In the case of complex power equipment, such as substation transformers, this is often not so. Typically, each unit is a 'one-off', whereas statistical methods are valid for a 'population'. Such a method is therefore unsuitable for power transformers and is normally not able to pick out 'weak' units.

To meet strategic and operative goals, it is essential to be able to identify the most vulnerable units and to choose, for each individual unit, the optimal replacement, maintenance and operation procedure. This calls for an individual approach.

Two examples of the individual approach are the *evaluation methods based on weighting* and the so-called *advanced evaluation methods.*

Weighting methods can be employed in the first phase of evaluation of power equipment. While simple and fast, they are subjective with regard to both the assessment and the input data and the weighting factors that are used. Because of this, the results offer limited physical or functional insight into a given equipment

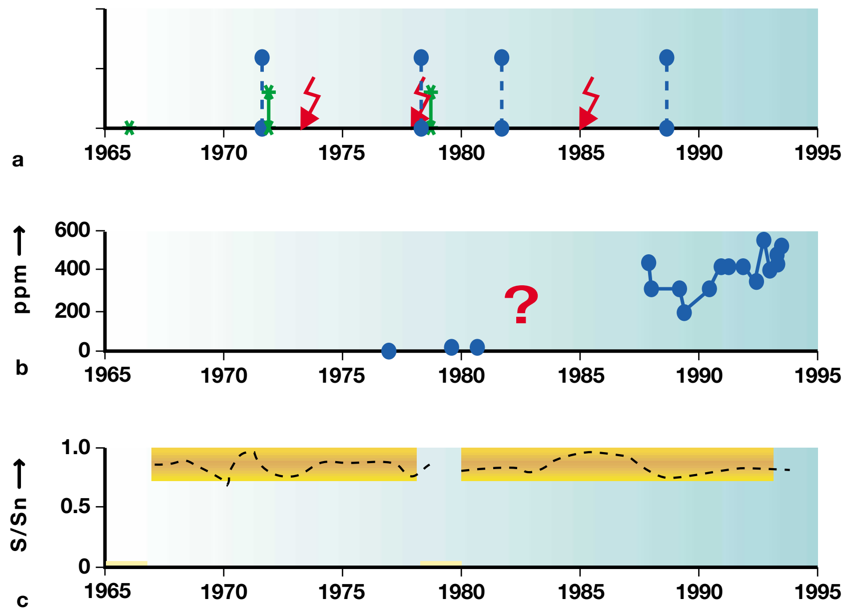
Table 1: Life assessment and condition evaluation can be used to support the most complex strategic planning decisions

Task \ Technology	Monitoring	Diagnosis	Life assessment
Incipient failure	**X**	x	
Failure	x	**X**	
Strategy	x Input data for LA	x Input data for LA	**X**

subsystem and may mix different stresses and risks.

Advanced evaluation methods can provide more objective information for decision support for the individual unit, but they depend on more detailed lifetime data being available. This data and the necessary know-how have to be combined into a general 'reasoning' strategy.

In the following, a look will be taken at how an advanced condition-based evaluation method developed by ABB is used to assess the lifetime status of power equipment, in this case power transformers.



3 Lifetime data sample for an old power transformer

a	*Operating events (red arrows)*	*Short circuits*
b	*Hydrogen in oil (ppm)*	*Repair work*
c	*Load (S/Sn)*	*Missing data*

Power equipment data

As mentioned, advanced evaluation methods depend on detailed lifetime data being available for the status assessment.

Over the entire life of a power transformer, or any other piece of power equipment, numerous factors will contribute, to different degrees, to changes in its functionality and operational capabilities. For the lifetime data of such a unit there are two main sources: the utilities and the equipment manufacturer. Some of the most important data stem from monitoring and diagnostics.

While the lifetime data are an essential element of every condition-based evaluation, the amount and quality of the data input – and also the processing details – will depend to a large extent on the utility's level of expectation. To ensure an in-depth and detailed condition-based evaluation, it is necessary to consider the main sources of transformer data and events over the equipment's lifetime.

In the case of power transformers, the main data stem from:

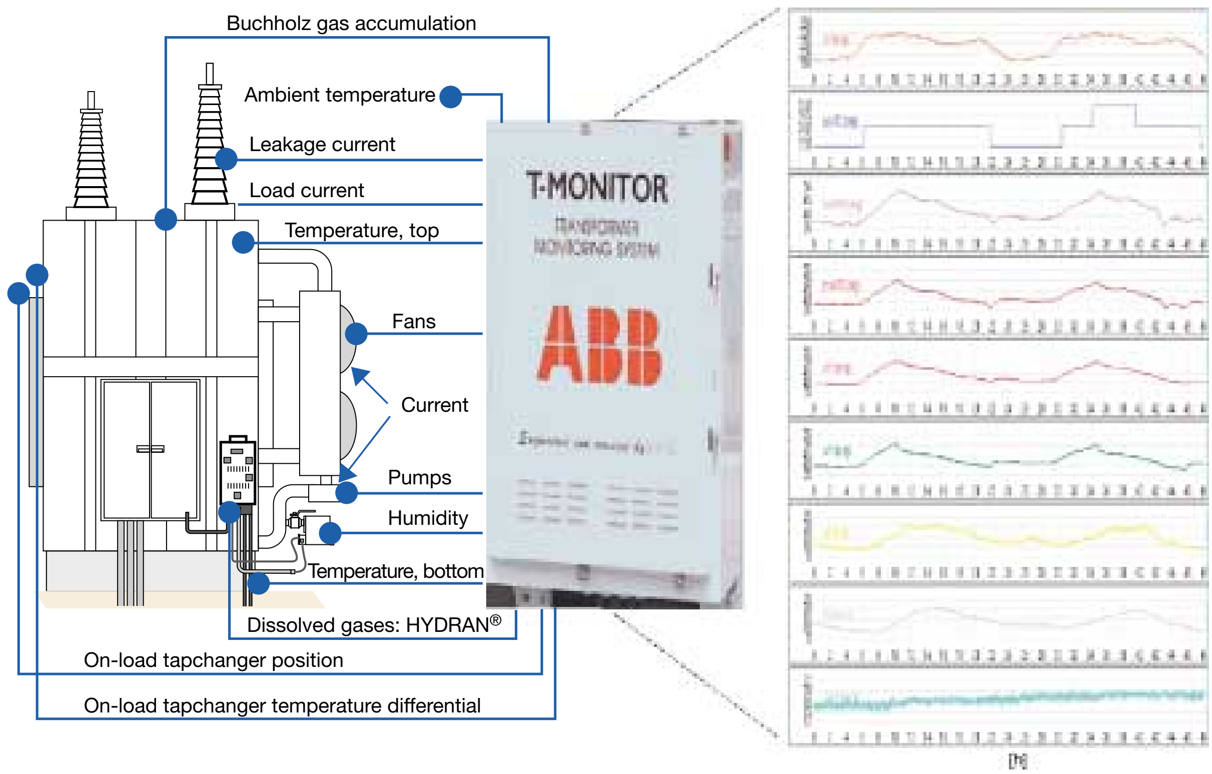
- Design and manufacturing
- Normal operation and environmental conditions
- Exceptional lifetime events in the power system
- Unit maintenance, relocation, repairs, etc
- Monitoring and diagnostics

Lifetime data can be heterogeneous, distributed, have various owners, be imperfect (ie, vague), indeterminate or incomplete. In practice, the available data is anything but perfect, and the older the unit the more difficult it is to obtain reliable and precise information for it 3.

Besides numerical data records and documents, lifetime information in language form can also be very useful. For example, the information 'almost full load' is valuable providing it comes from an expert in the field. Even estimates, such as 'low', 'high' or 'medium', etc, can be used. One of the goals during development of the condition-based evaluation support system was to be able to include even such imperfect data as this.

Monitoring systems are designed primarily to detect incipient failures. However, once installed, such a system is also a good source of data for condition-

4 Transformer monitoring systems are a valuable source of data on installed equipment



based evaluation and life assessment / management.

Monitoring systems, such as the T-Monitor from ABB 4, are also becoming increasingly powerful, and as more of them are installed the quality of available lifetime data will improve.

The reasoning behind advanced equipment evaluation

Three important things need to be considered when using an evaluation system:

- What is it that has to be evaluated?
- Which procedure or method is to be used?
- Which tools are needed for the different types of variables?

Suitability for use

The issues that need to be addressed in a life assessment evaluation are related to fundamental questions, such as 'What action should be taken, and with what priority?', 'Is it safe to continue operating a particular piece of equipment?', 'Should it be refurbished or replaced?', and so on.

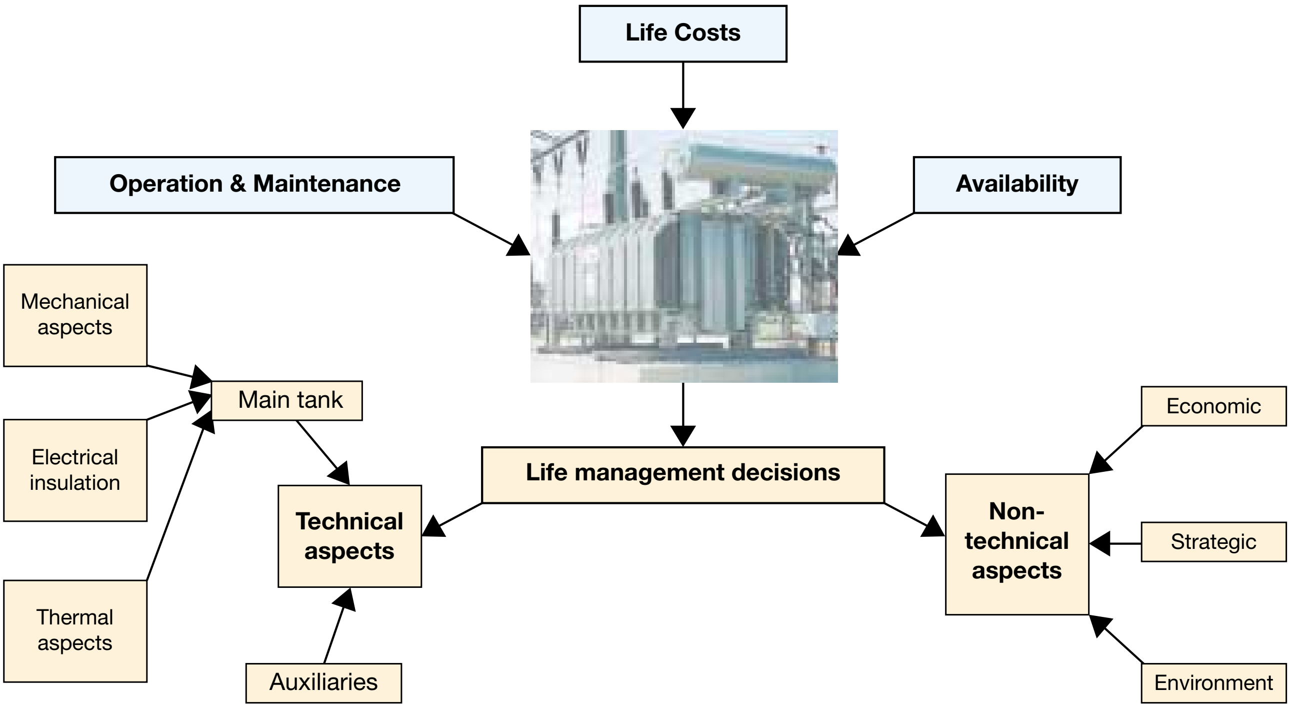
There has to be a clear idea about how such questions are defined, taking into consideration that not only an objective but also a cost-effective evaluation method is desired. The traditional *one-criterion* approach, which considers just the unit's age or just the paper insulation's condition, is no longer enough.

The key factor in the ABB method that was developed is the *suitability for use* of the individual asset, ie the suitability of a certain asset under specified operating conditions and at a certain location in the electrical system. The suitability for use is therefore related to the type of stresses acting on the equipment.

ABB developed a new holistic, unit-related evaluation concept which focuses on the equipment's functionality [1]. Both the technical and economic risks for the particular unit can be considered.

To perform an equipment evaluation based on condition and risk, knowledge is required of the design, operation, degradation and failure of the equipment.

5 Detailed consideration of condition and functionality in support of optimal life-management decisions for individual units



The unit has to be considered together with its sub-systems, material characteristics, operational influences and failure modes.

For example, it is necessary to define the risks which are important and the stresses that could jeopardize its functionality or suitability for use. The most important criteria for evaluation have to be identified and evaluation procedures developed for each of them. Information on a range of technical as well as non-technical aspects is needed. The evaluation is then carried out with respect to these aspects. This structured approach, shown in 5, aims at optimal life management decisions, the desired level of reliability and availability, optimized maintenance and lower lifetime costs.

The various aspects shown in 5 were further explored to obtain a set of detailed evaluation criteria. For example, one mechanical aspect that has to be evaluated in the case of a power transformer is the risk of failure due to excessive electromagnetic forces that could be caused by an external short circuit. Other evaluation criteria include the paper condition, aging of the general insulation system, electrical aspects and overloading.

In the ABB functionality-based concept, the defined set of criteria is assessed using a set of mathematical models and heuristics as basis. An assessment of the various criteria is performed for each unit and the present condition and capabilities are considered.

Condition-based evaluation procedure

To determine which evaluation criteria rules are required, it is necessary to first describe the model dependencies and the relationships between the known information. A sound understanding of engineering and manufacturing technology is needed to be able to formalize adequate functional relationships and reasoning strategies, taking into account the design and operating conditions.

The reasoning strategy can involve imperfect lifetime data and heuristic equipment knowledge and resembles the way a human expert would combine the offered items of information.

The steps ('rules' and reasoning techniques) that a human expert would use 6a for condition evaluation must be found and formalized.

The best way to emulate and implement such a complex, human-like inference process in a software environment is to use a knowledge-based system capable of considering the causalities, heuristic reasoning and influencing factors.

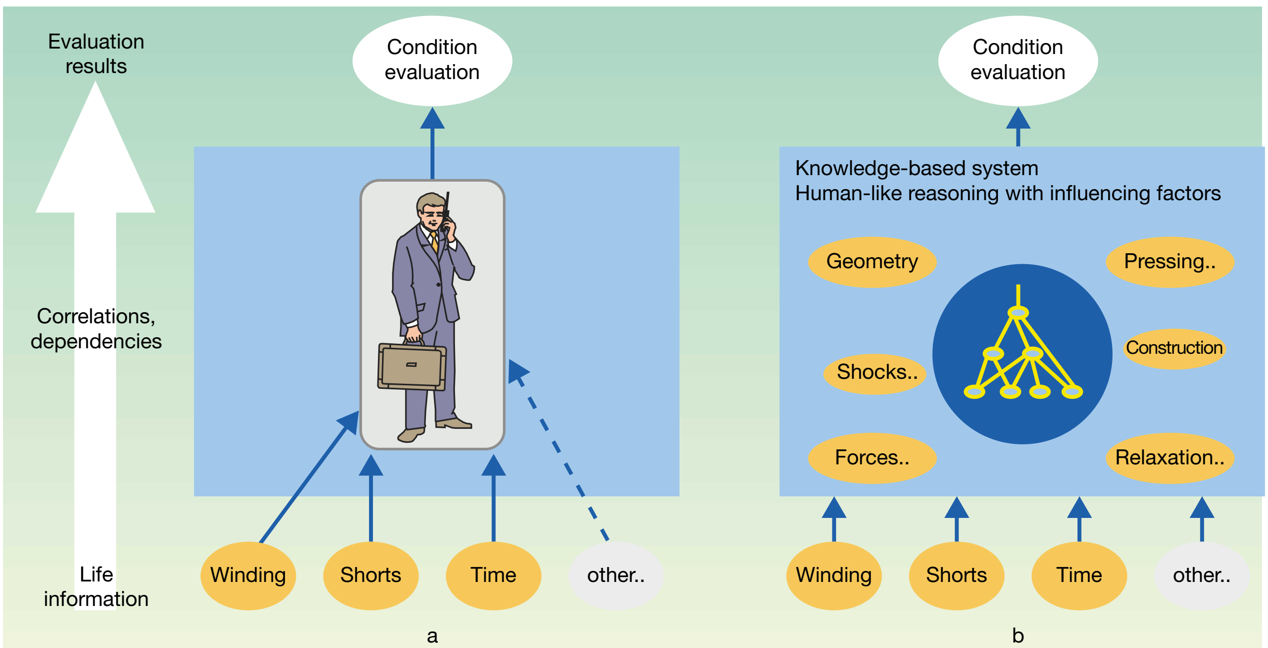
In the *example* shown in 6 the human expert considers the impact on a transformer winding – with a known winding design – of short-circuit forces after a given time in operation. He considers the available lifetime information and applies his knowledge and practical experience. In this example, aspects related to sudden possible changes in the winding geometry as well as long-time relaxation can be considered. The way human thinking is formalized into a knowledge-based system is shown in 6b. Additional influences can be added to describe the case in more detail, and various intermediary information can be derived.

The evaluation will yield an *evaluation score* for each transformer. This score is related to a condition, a capability, or a risk of failure, etc, and is used for comparing and ranking within a population. Recommendations regarding immediate action to be taken or forecasts of future equipment operation can also be supplied to the customer. However, the forecasts regarding the equipment's future, ie an estimation of its remaining lifetime, depend on future service conditions and events, and are therefore linked to objective uncertainties.

Use of precise and imperfect information

The functional and logical dependencies, rules and constraints used to describe human-like reasoning in the chosen methodology, are of a very general nature. They include 'if – then' rules from conventional logic, formulas and other crisp mathematical models, as well

6 **Condition evaluation by experts who make use of lifetime information (a), and with a knowledge-based system that describes human-like reasoning with causalities and influencing factors (b)**



as any premise-conclusion or input-output mathematical construct.

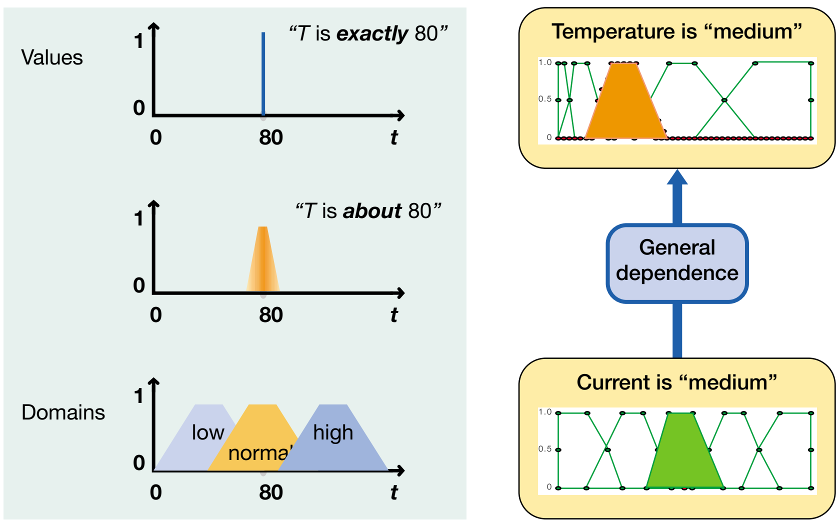
When carrying out a practical life assessment the equipment evaluation must be performed under imperfect conditions. Often, neither the available data will be complete or perfectly reliable nor can crisp models be found to describe the available knowledge. An advantage, however, is that it is also possible to use, besides crisp numerical information, vague statements about the transformer life events. Thus, a bigger pool of valuable information is available for the life assessment. Also, experience-based dependencies can be formulated in natural language.

Examples that show how such lifetime information and dependencies can be dealt with are given in 7. Linguistically formulated vague information, such as 'the temperature is *about* 80 °C', '*almost* full load', or 'the temperature is normal', etc, can be described using concepts from fuzzy set theory 7a. (For comparison, the description of precise information, such as 'the temperature is *exactly* 80 °C', in the same mathematical framework is also shown.) The x axis in 7a represents the temperature and the y axis shows to what extent a certain temperature value is *possible*. The values for x where the corresponding y value is zero are regarded as being *not possible* for the given verbal description. For instance, in 7a it is not possible for the temperature T = 0 to belong to the linguistic description 'T is about 80' or to the statement 'T is normal'.

7 **Calculation based on vague data and general dependency rules**

a *Description of vague input data and domains*

b *Example of processing using a general rule*



a b

Conventional mathematical approaches and models can be used to process the crisp information. Vague/uncertain data and a general dependence rule can also be processed, as 7b shows, where the dependence is described by linguistically formulated rules such as:

If the current is 'medium', then the temperature is 'normal'.

The values used for 'low', 'normal', etc, are described as shown in 7a. Inferred output values, such as 'the temperature is medium', shown by the trapeze in the upper part of 7b, can be converted to crisp numerical values or used as such in the evaluation process.

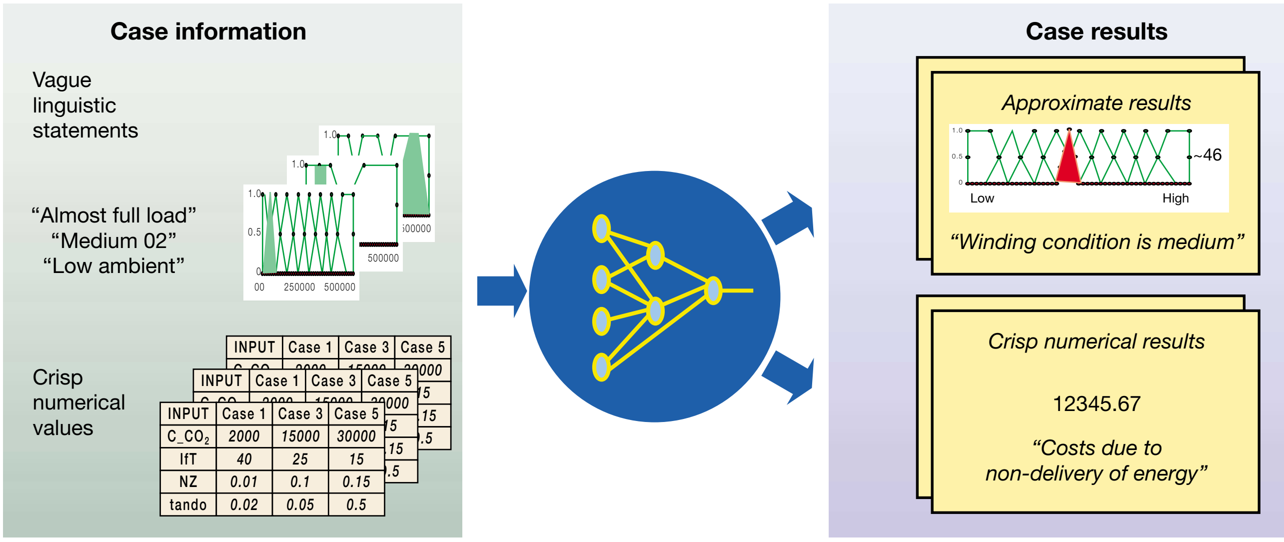
For more complex dependencies and interactions, multiple rules have to be described and combined.

Such rules can be formulated and tested using expert knowledge. The ABB condition-based evaluation and life assessment method [1] is based on detailed knowledge of transformer functionality.

Evaluation results

When applying the evaluation procedure to power transformers, the idea is to identify those transformers within a group which are most vulnerable and then rank them according to their suitability for use. In a first step, the input information for the evaluation has to be collated and prepared. The transformers' past history – from its manufacture right through to the unit's operation conditions – is then scrutinized to obtain a set of preliminary lifetime information. This information is often unstructured, unprocessed, heterogeneous and uncertain. Initial pre-

8 Crisp (precise) and uncertain (approximate) results of an equipment evaluation



processing provides the case-specific information 8 (left), which often includes, besides crisp numerical data, vague linguistic statements.

In the second step, certain criteria are evaluated using a knowledge-based system that is capable of handling heterogeneous and uncertain information 8 (middle). The results of this will be mainly in the form of crisp numerical values, but can also include approximate values, as shown on the right in 8. The approximate results indicate, on a low-to-high or bad-to-good scale, the area where a condition or a risk of failure is most likely to occur. An approximate numerical result, eg ~46, can also be derived.

The ranking with respect to a given evaluation criterion is straightforward when such results are available for a group of transformers. An example is shown in 9, which considers five transformer units. The results shown here are for two evaluation criteria: *general insulation aging* and *transformer core evaluation*.

The evaluation of the general insulation aging for these units 9a is based on data from a dissolved gas analysis and oil physical chemical tests. The results are shown as dark triangular shapes on a scale with arbitrary units, 100 indicating the worst result. On the right are numbers representing the corresponding crisp equivalents of these results. In a 'partial ranking', in which only one criterion – general insulation aging – is considered, transformer A exhibits the best condition. 9b shows the ranking for the evaluation of the core bolt heating in terms of how it increases the risk of failure.

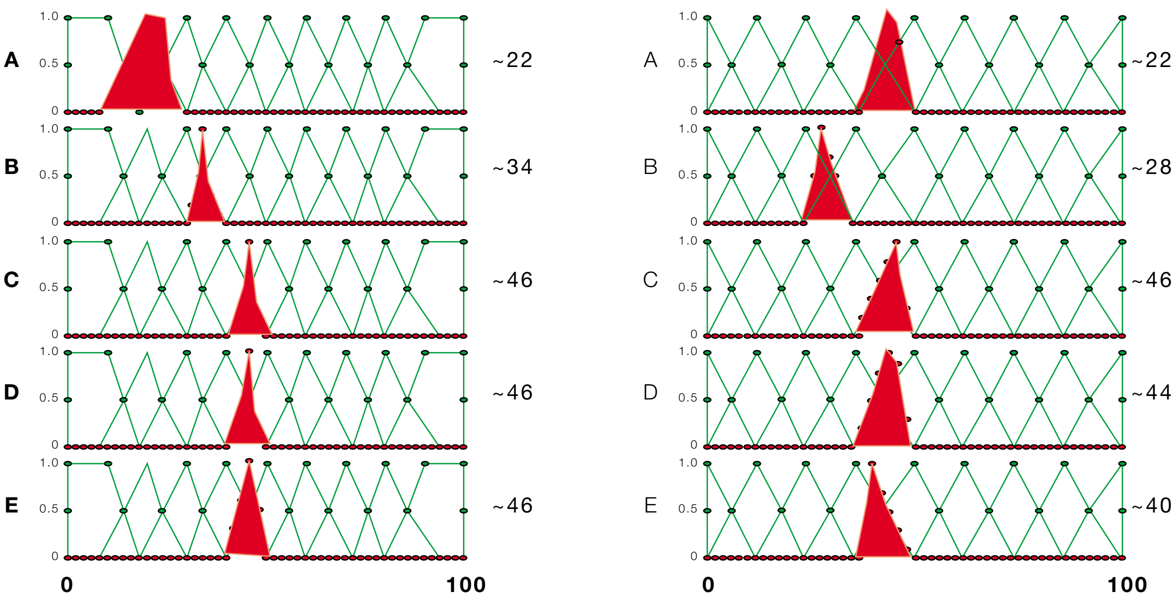
In the case of evaluation criteria related to external stress, the transformers can be ranked according to how well they withstand this kind of stress.

After considering a set of technically relevant evaluation criteria, the results can be combined to obtain an overall ranking, eg for the total technical risk of failure of the units. Several strategies exist for this, although they will not be dealt with here.

Table 2 summarizes the partial rankings deduced from the results seen in 9. The total technical risk was also derived under the assumption that the risk of failure due to general aging of the insulation and due to core heating is equally critical.

These rankings affect the order in which action needs to be taken. The transformers ranked with a '1' are most critical, and therefore have to be considered first. Thus, the ranking – partial or total – forms the basis for the

9 Examples of transformer evaluation. General insulation aging (a) and core evaluation (b)



condition-based decision on whether to carry out a replacement, repairs or maintenance.

Such a condition-based assessment can, of course, be extended further. It is seen that not all the transformers are equally critical, and that failure by some transformers will cause more consequential damage than failure by others. Therefore, in a final power equipment assessment, the strategic or economic importance of the units to the user could be considered as well. *Table 2* gives an arbitrary assessment of the units that were considered on a scale of 1 to 10, the score 1 representing the lowest and 10 the highest importance.

Decisions can be supported by combining the assessments based on technical aspects with those based on the importance of the units. If the total results of the technical evaluation are on a low-to-high risk scale of 0 to 100, and the importance varies between 0 to 10, a risk-importance diagram of the type shown in 10 can be obtained (this diagram is similar to the one used by ABB CALPOS-MAIN). The units A to E are the same as those in *Table 2*.

A special critical case, denoted by X, is shown as an example.

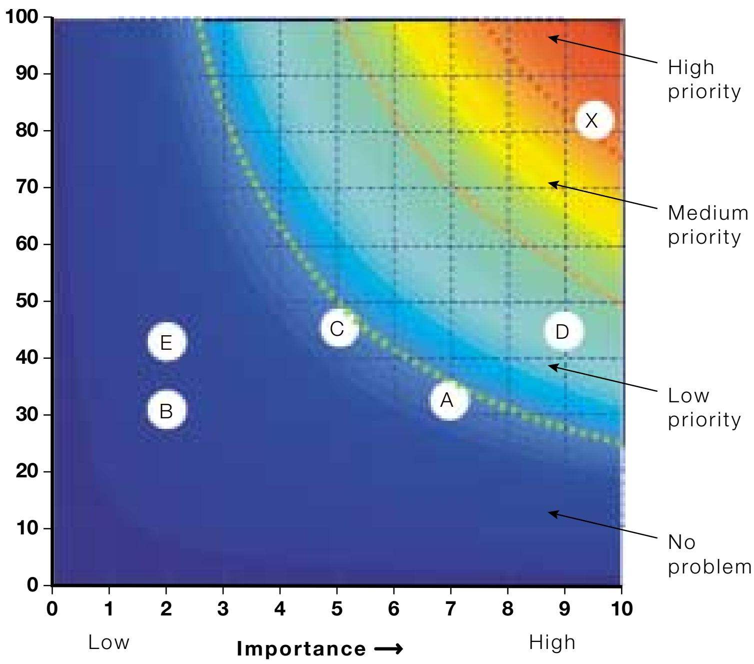
Various areas in the risk-importance evaluation diagram can be delimited based on experience and users' preferences. Four such areas are shown in 10: 'high priority', 'medium priority',

Table 2

Transformer ID	General insulation aging	Core assessment	Total technical condition or risk	Importance of transformer unit
	Ranking	*Ranking*	*Ranking*	
A	3	1	3	7
B	2	3	4	2
C	1	1	1	5
D	1	1	1	9
E	1	2	2	2

*) The ranking '1' represents the worst case within the group under consideration, ie the first unit that requires attention.

10 Combined equipment assessment considering total technical risk and equipment's importance. A to E refer to individual transformer units.



'low priority' and 'no problem'. The transformer units considered are denoted by A, B, C, D and E.

Units which fall into the top-right area are both important and 'high risk' in terms of failure. These have to be considered first. They need special attention and require action with high priority.

At the other end are the 'no-problem' units. Of the transformers considered only unit D needs attention, but units A and C are also close to defined limits. Units B and E can be considered ok at the time of evaluation, whereas unit X requires immediate attention.

Various other force-related and electrical and thermal criteria can be evaluated using the developed method, as can economical and environmental aspects. Together, the derived criteria, ranking values and total assessment of risk and conditions give a detailed and objective insight into each considered unit, and hence the best possible and most objective support for decision-making.

Adding value through lifetime management

The objective information provided by condition–based evaluation of power equipment supports life management decisions that can add value to a utility's operations.

Such information may include the risk of failure due to certain types of stress, the present capabilities of the equipment, and the relative comparison (ranking) of the equipment within a population. Recommendations concerning operation, repair, up-rating or replacement are another source of added value for utilities.

Life assessment evaluations performed for major utilities in Europe and North America have convincingly shown that the developed tools offer an objective platform for life management of installed assets.

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