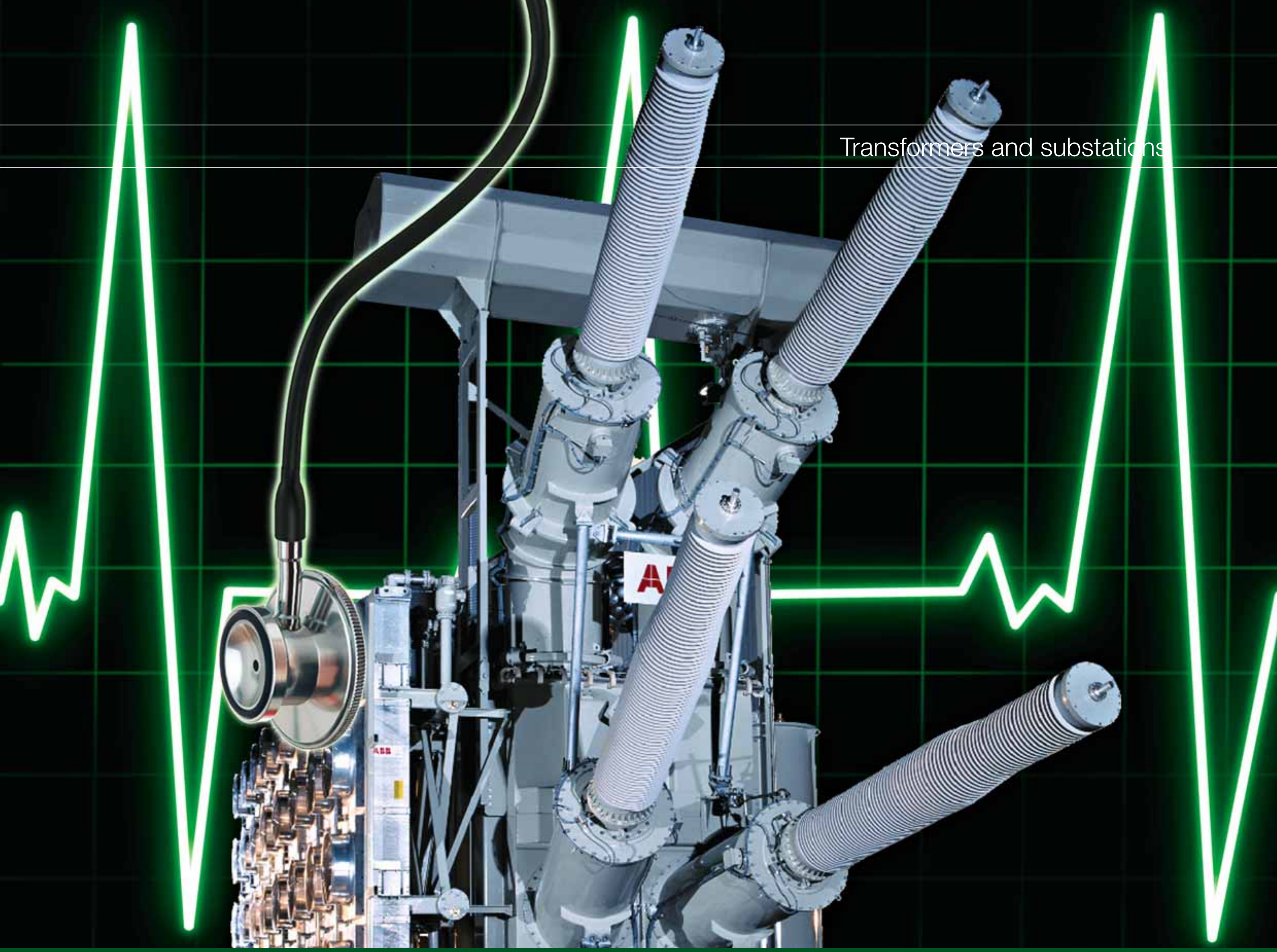


Transformer challenges

Condition monitoring is becoming a strategic tool for utilities

Lars Pettersson, Lena Melzer, Claes Bengtsson, Nicolaie Fantana

As crucial components in electrical grids, transformers are built to the highest standards of precision and quality and designed for a long lifetime. As the average age of these transformers is in the range of 30 to 40 years in many countries, the probability of malfunction is on the rise.

This situation is accentuated by the trend to operate transformers closer to their performance limits, adding to their vulnerability if adequate countermeasures are not taken.

The replacement of a failed transformer is not a matter that can be completed within days. This makes it all the more important to minimize the probability of such an event. This article explores how ABB can help utilities gain a greater insight into the health of ageing transformers and so achieve a better management of their assets.

Transformers and substations

To optimize their replacement and refurbishment strategies, utilities need to evaluate the condition of their transformer fleet [1,2]. The spectrum of technical measures for a utility to manage a population of transformers covers three areas:

- Detection/prevention of incipient failures by means of supervision and monitoring
- Identification of malfunction/fault by diagnostic evaluation and
- Strategic planning for repair, replacement, etc. by condition assessment and fleet screening.

Modern monitoring systems, such as ABB's TEC (Transformer Electronic Control), not only aim to detect faults but also provide data collection functionality for condition assessment.

Besides using direct measurements, the diagnostic evaluation relies on theoretical considerations drawing on ABB's in-depth knowledge of transformers and on modern design tools. Application examples are advanced frequency response analysis, dielectric response measurements and calculations of short-circuit strength and overloading capability.

The condition assessment and fleet screening functions support strategic decisions related to both single units and larger populations. The data used are drawn from design, operational history and diagnostic measurements and evaluation.

ABB has the expertise to assist transformer owners in all these areas but can also help with various advanced on-site activities such as repairs or upgrading [3,4]. In order to illustrate the practical application of ABB's transformer condition assessment, this article presents three cases. They cover:

- Strategic planning or fleet screening
- Transformer life extension
- Supervision of a suspect unit

Evaluation for strategic planning

The objective of strategic evaluation of a population is to identify the most vulnerable units so that maintenance or replacement activities for those units can be prioritized. For the strategic evaluation two different approaches can be taken:

- Statistical analysis, mostly with transformer age as the major independent variable
- A unit oriented method to determine the condition or withstand strength of each individual unit

While the statistical analysis often serves as a useful first step, the individual and unit-oriented approach is required in most cases.

Fleet screening: influential factor method

This evaluation involved 49 net transformers, rated between 40 and 100 MVA. Various influential factors having a bearing on the life expectancy of the transformers were identified. Each transformer in the population was then evaluated and assigned a relative score for each of the factors.

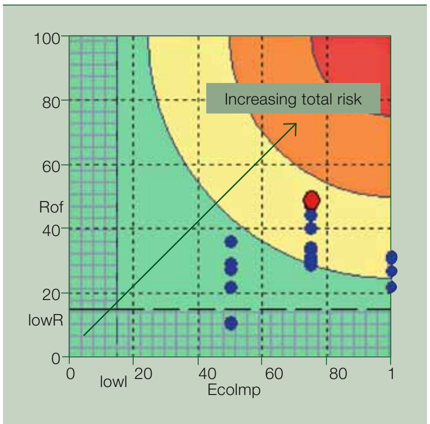
The score value is a number between 0 and 100, with 100 indicating the worst and most severe condition for the factor being looked at.

Because some influencing factors are more critical than others, a weighting value was additionally assigned to each influential factor.

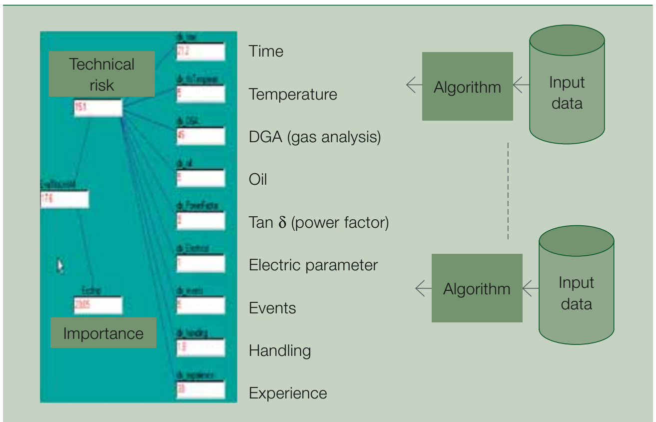
The overall indication for a potential technical risk for a particular transformer was then determined by combining the individual scores – either as a weighted sum or by using the maximum value of the individual scores.

The influential factor evaluation method used here is illustrated in 1 and is based on accessible parameters. Some of these pertained to a general historic

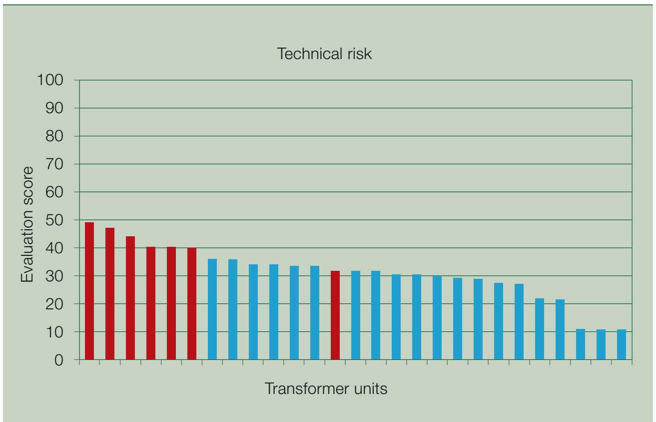
3 Total result of the ranking. The device marked in red presents the highest risk.
Rof: technical risk potential
EcoImp: economic relevance



1 Transformer screening uses algorithms based on data that are easily determined and defined. These data are expressed as scores between 0 and 100.



2 Technical risk indication based on the weighted value approach. The devices shown in red are at the highest risk.



degradation, others are directed towards thermal wear, possible extraordinary events, repair status and experience. Finally, there is a group of data related to the actual condition of the transformer determined by DGA (dissolved gas analysis) and oil analysis.

For the 49 transformers investigated, data were available on rating, age, load, ambient temperature and DGA results. For some units, information also existed on design and on extraordinary events. Oil analyses were available for 27 units. Hence, two rankings were performed – one ranking involved the latter 27 units and the other included all 49 units without considering the oil analyses.

The results of the ranking of the technical risk indication of the 27 units using the weighted score approach is presented in 2. The six transformers to the left are at highest risk.

If the analysis is supplemented with an evaluation based on the maximum parameter value instead of the weighted value, one more unit (also marked red in 2) is added to the "high potential risk" group.

The high risk group is characterized essentially by higher degradation of oil and paper insulation. Age alone, however, did not determine the ranking order.

The overall exposure for a utility does not only consist of the technical risk but it also depends on the economic consequence of a possible fault, eg, cost of non-delivered energy, cost of repair. Hence, an economic parameter referring to this consequence is defined with a relative value between 0–100, provided directly by the utility.

A combined view of technical risk potential (Rof) and economic relevance (EcoImp) is shown in 3.

Although a significant ranking was obtained, the DGA information indicated that the risk of an imminent failure was low in this population. However, for some of the transformers, oil treatment was recommended and a deeper analysis of the ageing status was later performed on the unit with the highest assessed risk.

The condition assessment and fleet screening functions support strategic decisions related to both single units and larger populations.

As an alternative to the view in 3, a risk index can be defined as the normalized product of the technical risk and the economical parameter. The risk index can be seen as a measure of the expected consequential cost of a failure, a value that in some sense is related to an insurance risk premium.

Fleet screening: rule-based approach

In a more detailed and structured evaluation, the aim is to determine either the condition of the transformer, the condition of its sub-components or its withstand strength against specific external stresses. The various sub-components or stresses such as thermal, mechanical or electrical stress as well as the loadability are analyzed individually. A separate evaluation score (or potential risk of failure) is associated with each of these sub-components/stresses. In an overall evaluation the sub-scores may be combined into a total score 4.

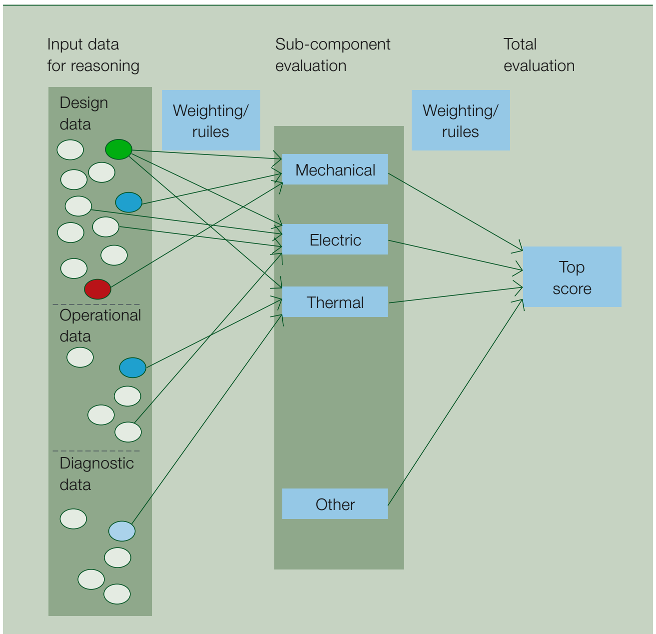
The method of deducing an evaluation score for a sub-component may be based either on a combination of influential factors, addressing only that particular stress/condition, or it may be a rule-based reasoning model reflecting deeper transformer knowledge. In a structured evaluation, a parameter value may enter into the evaluation of several sub-components. For instance, time-in-operation not only affects the ageing of paper but also the relaxation of the clamping force in windings. The interpretation of DGA results is relevant in both the electrical evaluation and in the thermal evaluation.

In one of the case studies discussed here, thirteen 220 kV substation transformers, manufactured between 1969 and 1998, were investigated. Their ratings varied between 63 and 315 MVA, with one 400 kV/500 MVA unit also being included. Some units were free-breathing while others were sealed with a rubber diaphragm. All units but one had an on -load tap changer and all but one had a short-circuit impedance between 10 and 12 percent, with the exception of unit number 3 which had an impedance of 22 percent.

The following subcomponents were evaluated in this assessment:

- Short-circuit strength (determined from buckling and tilting strengths)
- Electrical risk (deduced from design parameters, oil analysis and DGA results)
- Thermal ageing of paper
- Overall heating of insulation (deduced from oil and DGA analyses)
- Core heating
- Loadability of the transformers (short time and long time emergency loading capability)

4 The structured model used to evaluate a transformer's risk



Some of the aspects were evaluated using rules while other parameter scores were determined from influential factors. The results of the ranking with respect to short-circuit strength and loadability are shown in 5 sorted by year of manufacture.

The evaluation shows that

- Both types of evaluation categorize the transformers into 4–5 subgroups
- Units 2 and 5 have the highest risk at an external short-circuit event but are less stressed at overloading
- Unit 3 (with the highest impedance) has the best short circuit strength but the lowest loadability
- Comparing the units with 10 to 12 percent impedance shows that the newer ones have a better short-circuit strength than the older ones
- no clear time dependence in the loadability is visible

The other sub-parameters were evaluated in a similar way.

In the case presented, the working condition of all evaluated transformers was good. However, if exposed to special extraordinary events (short-circuits or overloads) transformer units 2, 3 and 5 could be in danger.

ABB has performed several evaluations, both with the influential parameter method and the structured rule-based approach in Europe and in USA [5,6,7,8].

Life extension study

A life extension investigation involves an evaluation of the present condition of the transformer and an estimation of the "remaining" life of the insulation under given assumptions about the future service.

Fleet screening can be done with rule based or influential factor methods.

The present condition is normally determined from an assessment of the immediate risk of failure, determined by the DGA and oil analysis, and an estimation of the "consumed" life of the insulation. Information about previous events that may have stressed the transformer is also taken into account. Electrical and mechanical risks have to be evaluated as well.

In the case presented here, the transformer was a generator step-up (GSU) transformer manufactured in 1979. It was free breathing and oil-forced water-forced (OFWF) cooled. The transformer had insulated bus ducts on the low voltage side. The average load was 78 percent of rated load but during the years it had varied between 35 percent and 100 percent.

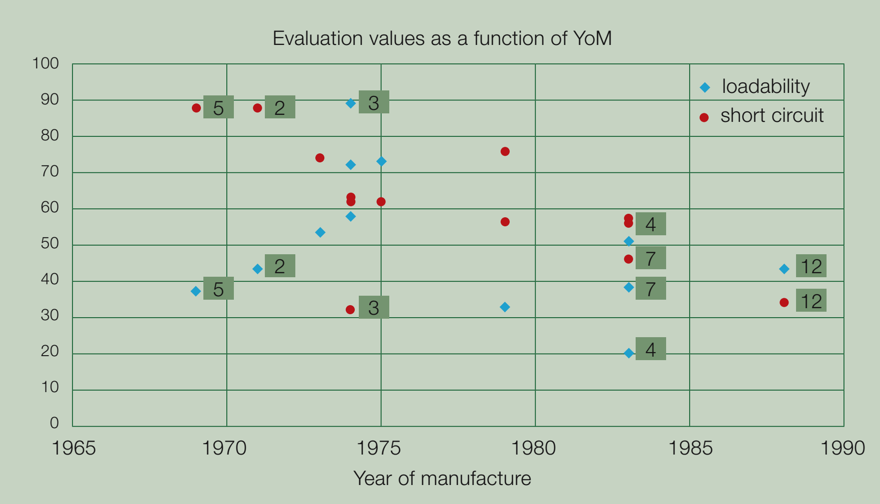
The transformer had been exposed to some minor events – causing gas alarms – and one, more severe, extraordinary event: a one-phase earth fault on the high voltage side producing high currents through the transformer.

The results of this investigation were as follows:

- Oil and DGA analyses showed a low immediate risk of failure.
- Estimation of the ageing of the paper insulation at hot spot indicated a DP – value around 350 (see Factbox).
- Ageing of oil was low but it was expected that the inhibitor would be expelled in another seven or eight years with the same future thermal stress. Hence, a recommendation was given to treat the oil, preferably using oil reclaiming, within five years.
- The short-circuit strength of the transformer did not fulfil the present ABB standards, especially regarding the buckling strength of the low voltage winding. The calculations showed that an external single phase high voltage to earth fault could stress the transformer to the limit or beyond.

In conclusion, the short circuit strength was limited but the transformer was otherwise in acceptable condition. Due to the limited short circuit capability the transformer was replaced.

5 Ranking of the units as a function of year of manufacture (YoM). The numbers in the boxes refer to individual transformers. A higher, ordinate score means a higher relative risk.



Factbox The DP

The DP (degree of polymerization) is the average number of glucose monomers of the cellulose molecule. It is related to the mechanical strength of the insulation paper and its decline is hence a measure of the paper degradation. The DP value at the winding hot spot location can be estimated if the temperature, deduced from the as-designed temperature profile and service data, is known together with data from oil analysis and DGA.

Evaluation of a suspect unit

This case concerns a medium-sized 50 MVA GSU transformer, OFWF-cooled and free-breathing, manufactured 1962 and located indoors.

In the DGA evaluation acetylene (C_2H_2) had been detected, indicating a possible internal fault.

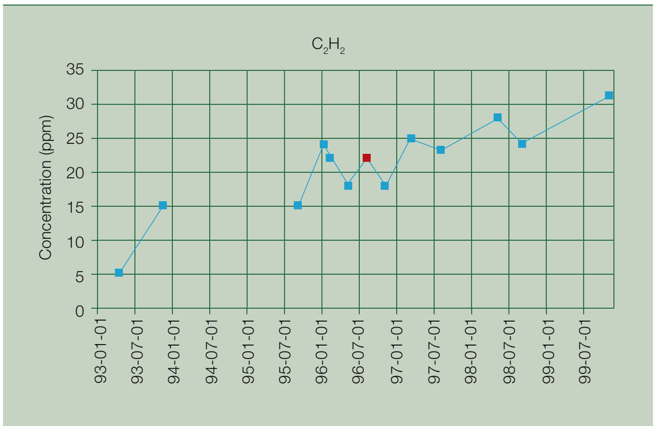
The temporal development of acetylene, showing small incremental jumps, is shown in 6. The red point in the graph indicates the start of the diagnostic evaluation.

The levels of the other hydrocarbons were low and practically constant, the carbon oxides indicated a somewhat aged transformer but their concentrations were not exceedingly high. Finally, the hydrogen level was low and constant.

Life time extension, upgrading and risk reduction have an immediate effect on the bottom line of the utility business.

Increasing acetylene concentration is an indication of electric discharges in the oil, supported by the overall DGA gas pattern showing almost no cellulose content. Discharges of this type are often due to a local charging/discharging effect of a metallic piece in the transformer.

6 Evolution of acetylene (C_2H_2) found in the main tank of a monitored transformer



To find the root cause of these possible discharges, the design of the transformer was scrutinized in detail, a more complete oil analysis was performed and acoustic and electric PD (partial discharge) measurements were performed on-site.

The PD measurements showed strong electric discharge pulses. The discharge pattern resembled the pattern of streamer discharges propagating in oil. The acoustic measurements found two acoustic sources, but no definite localization of the source could be made.

Possible sources of these discharges were a shield on floating potential located around a LV-lead or PDs between core and tank. As these did not impose an immediate danger to the transformer, it was recommended to keep it in service with frequent DGA analysis. Based on this recommendation the transformer was kept in service for another couple of years. A subsequent analysis of the transformer after it was taken out of service confirmed the source of discharges.

A valuable service for utilities

The cases presented demonstrate how a careful condition assessment, on the fast track or very detailed, helps utilities to manage the ageing fleet of transformers. Other important aspects such as the possibility of upgrading transformers have been addressed in condition evaluation studies as well. Life time extension, upgrading and risk reduction have an immediate effect on the bottom line of the utility business and preventive monitoring pays off immediately.

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