SUMMARY

Power equipment such as turbines, generators, transformers, switchgear and cables represent a major capital investment in power stations and grids. With a high duty-cycle, or repeated short duration overloading, aging of such components may be appreciable. In practice, however, many components perform well even after their depreciation term has expired. As a result extension of service time is a serious option for reduction of investment costs. On the other hand, life extension may increase the risk of failure, depending on the operation and maintenance practice. Adequate condition assessment (CA) enables to determine effective strategies for operation, maintenance and replacement, thereby avoiding technical and economical catastrophes.

This paper describes the methodology of determining both the technical and the economical condition of power transmission and distribution components. We first elucidate the technical, strategic and economical aspects of component condition. We will further discuss our approach in assessing the technical condition and the economical condition, and the ways to integrate assessment activities in a maintenance program.

The steps in assessing the technical condition are:
- inspection and/or on-line diagnostics
- analysis of historical data
- selection and application of advanced (off-line) diagnostics
- interpretation

An effective assessment procedure however requires a development phase consisting of the following steps:
- Failure mode effect and criticality analysis
- understanding mechanisms of failure by defects and degradation, and identification of indicators
- development of diagnostic tools to measure these indicators
- assessment tools to interpret the measured indicators and determine the actual condition and its consequences in terms of maintenance need.

We will present an overview of indicators and measuring technologies for power transformers and high-voltage switchgear. The last step (interpretation) involves setting-up databases and analysing trends (for example by datamining techniques), in combination with background knowledge and O&M performance data.

After an assessment procedure is developed, it should be integrated in a maintenance program, and include a permanent learning cycle in order to continuously learn from experience and improve performance and cost-efficiency. We will show how condition assessment activities may support decisions on appropriate maintenance, and yield information on remaining life.

The economical assessment described consists of an integral Life Cycle Cost Analysis involving:
- Capital investment
- Operational costs
- Maintenance costs
- Failure costs

We will discuss the approach adopted, and show how knowledge on the technical condition may serve as the basis of an economical evaluation. We will finally present two possible applications: the first one is to determine and plan the specific maintenance needs, the second one is to determine the economically optimal replacement age.

In conclusion, it is stated that condition assessment requires both diagnostics and tools for adequate interpretation, working together in a so called “learning cycle”. KEMA has developed systems for periodic inspection (on-line / off-line) of the most important components in power transmission and distribution networks and has integrated these into a complete condition based maintenance supporting tool, including diagnostics, interpretation, Life Cycle Costing and data management tools. KEMA has developed numerous references, norms, trends and knowledge-based rules to classify the measured data and to relate these data to practical advice ranging from direct maintenance actions for repairable defects to investment decisions and O&M policies for aged equipment.
INTRODUCTION

Power equipment such as turbines, generators, transformers, switchgear and cables represent a major capital investment in power stations and grids. With a high duty-cycle, or repeated short duration overloading, aging of such components may be appreciable. In practice, however, many components perform well even after their depreciation term has expired. As a result extension of service time is a serious option for reduction of investment costs. On the other hand, life extension may increase the risk of failure, depending on the operation and maintenance practice, see e.g. Bloemhof and Knijp (1). Adequate Condition Assessment (CA) enables to determine effective strategies for operation, maintenance and replacement, thereby avoiding technical and economical catastrophes.

Before elaborating on CA-techniques, we specify three different types of condition relevant to power transmission and distribution equipment: technical, strategic and economical condition.

The technical condition

The technical condition of power T&D equipment accounts for dielectric, thermal and mechanical phenomena. The dielectric condition is related to the capability of the insulation to withstand high voltages and fields. The thermal condition is related to the capability of handling the required power and the mechanical condition is related to the capability to carry out the specified movement (tap-changer, switchgear) or to withstand (electro-magnetic) forces and vibrations. In general the technical condition of the component is defined by the degree in which it performs according to its specification (nameplate rating). The technical condition may best expressed in an instantaneous failure rate. Typically, this failure rate decreases the first few years due to superseded teething effects (defects related to materials, construction and installation of the component). After that it may be approximately constant for many years due to unpredictable and more or less unavoidable failures. Eventually, wear and aging result in degradation and cause a gradual increase of the failure rate.

The strategic condition

The strategic condition accounts for the function of the component in the grid. It is defined by the degree in which the nameplate ratings, the design or the technical condition meet the specifications of the adopting grid (e.g. regarding power levels), and comply with legislation (e.g. regarding safety and environment). It also depends on the availability of spare parts for replacement. A technically perfect component may have an unacceptable strategic condition. Decisions related to strategic conditions require input from utilities and manufacturers, next to legal data, and are often based on prognosis.

The economical condition

The economical condition accounts for the overall costs of investment, operation, maintenance and failures over a specified time interval. Here failure costs consist of component revision or replacement, non-delivered energy, breach of contract etc. The economical condition may be assessed by an evaluation of different Life Cycle Cost scenario’s based on the present technical condition. Typically, such scenarios involve decisions about lifetime extension, as well as on operations and maintenance optimization. Note that also delivery times of spare parts or components are part of the economical condition.

This article describes the methodology of determining both the technical and the economical condition of power equipment. We first describe the sequence required for assessing the actual technical condition: interpretation of available data, selection of inspections and diagnostic tools, setting-up databases and the use of datamining techniques. Subsequently, we will present two applications: the first is to determine an optimum maintenance strategy, the second one is to determine an optimized replacement scenario.

ASSESSMENT OF THE TECHNICAL CONDITION

The technical condition of a component is made up of repairable defects as well as by (economically) non-repairable degradation. Repairable defects directly indicate the need for maintenance and specifies the maintenance action required. Degradation relates to the remaining service life.
Assessment of the technical condition in terms of dielectric, thermal and mechanical aspects involves at least one of the following activities:

- Inspection and / or on-line diagnostics
- Analysis of available relevant historical data (operational, maintenance, diagnostics)
- Selection and application of advanced (off-line) diagnostics and / or sample taking

In order to perform a justified interpretation (assessment) these activities are preceded by a sequence of 4 stages, for each component:

1. Failure Mode Effect and Criticality Analysis
2. Understanding mechanisms of failure by defects or degradation, determination of relevant indicators and failure levels
3. Development of diagnostic tools to measure the indicators
4. Assessment tools to interpret the measured indicators and to determine the actual condition and possible consequences (in terms of the maintenance need).

Figure 1 shows an example of a failure distribution for power transformers and switchgear, and the development stages for power transformers assessment tools. Below the four stages are further elucidated.

<table>
<thead>
<tr>
<th>Power transformer</th>
<th>Low oil MV switchgear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulator 5%</td>
<td>Other 36%</td>
</tr>
<tr>
<td>Tap changer 55%</td>
<td>Busching 5%</td>
</tr>
<tr>
<td>other 36%</td>
<td>Core 4%</td>
</tr>
</tbody>
</table>

1) Failure Mode Effect and Criticality Analysis

The first step is to pinpoint the critical failure modes of the component. This is typically achieved by an expert review of the design and by correlation to failure statistics. Often one single failure mode is predominant and should be focussed upon.

2) Understanding mechanisms

Understanding is extracted from physical models, field experience and (accelerated) aging tests in laboratories, in combination with the component design and operation. From this the relevant indicators are derived. For instance if the tap-changer is the most critical element and contact carbonization is the mechanism of deterioration, then the contact resistance is the most obvious indicator. The corresponding failure level can be obtained by analyzing failure and diagnostic data.

3) Diagnostic tools

Indicator values are obtained by

- inspections
- sample-taking
- diagnostics
- monitoring

Inspections consist of visual perception and possible additional quick (on-line) diagnostics like thermal imaging. Observation takes place while components are in service. In addition sample-taking is an effective way to determine the level of degradation. However, except for oil samples, this method is destructive and often requires the dismantling of the component, which is a major operation and requires the component to be taken out of service. Diagnostics often involve more advanced equipment, requiring expert handling as the indicator often gives an indirect measure of the aging process. DGA is a good example for an quick on-line but indirect diagnostic, tap-changer contact resistance is a good example for an off-line but direct diagnostic. Monitoring (sampling of indicator values) is always on-line and continuous, whereas diagnostics result in an assessment of the condition at one single moment only.

Power station equipment like turbines and generators, the remaining substation equipment like protection equipment, voltage- and current transformers, busbars, disconnectors, surge arrestors and cables plus accessories, towers and lines are treated in a similar fashion but fall outside the scope of this article.

The selection of inspection items, on-line and advanced diagnostics is based upon the required accuracy of the assessment and is often based on a first indication from the analysis of the relevant historic operational, maintenance and diagnostic data.
### Table 1 Indicators for power transformers

<table>
<thead>
<tr>
<th>ACTIVITY</th>
<th>INDICATOR</th>
<th>TECHNIQUE</th>
<th>DIRECT</th>
<th>IN SERVICE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inspection</strong></td>
<td>sound level, vibrations, vegetation, coating, deformation, oil levels, temperature indicators, color of breather (if applicable), nearby surge arrester operations, tap-changer operations, oil leakage, cooling fans, cabling and cable trays, protection equipment, corrosion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Diagnostics</strong></td>
<td>Key gases</td>
<td>DGA</td>
<td>no (thermal, dielectric)</td>
<td>yes</td>
</tr>
<tr>
<td>General</td>
<td>Oil condition</td>
<td>OA</td>
<td>yes (dielectric)</td>
<td>yes</td>
</tr>
<tr>
<td>Tap changer</td>
<td>Partial Discharges</td>
<td>PDA</td>
<td>yes (dielectric)</td>
<td>yes</td>
</tr>
<tr>
<td>Key gases</td>
<td>DGA</td>
<td>no (thermal, dielectric)</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Contact resistance</td>
<td>TDS</td>
<td>yes (electrical)</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Power of driving motor</td>
<td>TDS</td>
<td>yes (electrical)</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Bushings</td>
<td>Tan δ and capacitance</td>
<td>Loss angle</td>
<td>yes (electrical)</td>
<td>no</td>
</tr>
<tr>
<td>Core</td>
<td>No-load losses</td>
<td>Loss angle</td>
<td>yes (electrical)</td>
<td>no</td>
</tr>
<tr>
<td>Windings &amp; paper</td>
<td>CO₂ concentration</td>
<td>DGA</td>
<td>no (mechanical)</td>
<td>yes</td>
</tr>
<tr>
<td>Tank &amp; connections</td>
<td>Furfural concentration</td>
<td>FA</td>
<td>no mechanical</td>
<td>yes</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>RM</td>
<td>yes (electrical)</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Contact resistance</td>
<td>TI</td>
<td>no (thermal)</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Stray fields</td>
<td>TI</td>
<td>no (thermal)</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

1) Although the underlying cause is often of a mechanical nature (deformation) or electrical / chemical nature (material deterioration) with thermal consequential problems.

2) The mechanical strength of paper is expressed by degree of polymerization (DP). By aging, a chemical process, the DP-value decreases. Both the CO₂ concentration and furfural analysis provide for an indication of this DP-value.

### Table 2 Indicators for HV-switchgear

<table>
<thead>
<tr>
<th>ACTIVITY</th>
<th>INDICATOR</th>
<th>TECHNIQUE</th>
<th>DIRECT</th>
<th>IN SERVICE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inspection</strong></td>
<td>sound, vegetation, deformation, number of switching operations, vibration of bushings, spacers, connections, secondary equipment, leakage, corrosion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Diagnostics</strong></td>
<td>SF₆ condition</td>
<td>GA</td>
<td>no (thermal, dielectric)</td>
<td>yes</td>
</tr>
<tr>
<td>General</td>
<td>Oil condition</td>
<td>OA</td>
<td>yes (dielectric)</td>
<td>yes</td>
</tr>
<tr>
<td>Vacuum condition</td>
<td>VLT</td>
<td>no (electrical)</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Mechanism</td>
<td>Contact velocity</td>
<td>SDS</td>
<td>yes (mechanical)</td>
<td>no</td>
</tr>
<tr>
<td>Vibrations</td>
<td>SDS</td>
<td>yes (mechanical)</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Trip coil current</td>
<td>SDS</td>
<td>yes (mechanical)</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td><strong>Dielectric</strong></td>
<td>Partial discharges</td>
<td>PDA</td>
<td>yes (electrical)</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Primary</strong></td>
<td>Contact resistance</td>
<td>RM</td>
<td>yes (electrical)</td>
<td>no</td>
</tr>
<tr>
<td>Circuit</td>
<td>Contact resistance</td>
<td>TI</td>
<td>no (thermal)</td>
<td>yes</td>
</tr>
</tbody>
</table>

DGA = Dissolved Gas Analysis  TI = Thermal Imaging  OA = Oil Analysis  FA = Furfural Analysis  GA = Gas Analysis  VLT = Vacuum Leakage test  SDS = Switchgear Diagnostic System  PDA = PD analysis  RM = Resistance measurement  TDS = Tap Changer Diagnostic System

4) Assessment tools
The results gained from monitoring and diagnostic tools require expert interpretation. Assessment tools for this stage involve pattern recognition and fingerprint techniques (both regarding deviations from known reference patterns), trend analysis, knowledge-based rules (from field and laboratory tests and theoretical experience) and (results from) datamining. The combination with the (background) knowledge gained from the analysis of O&M data will sharpen the assessment by emphasizing the results of certain diagnostics. For example when a transformer experiences many system short circuits, the insulation paper quality becomes highly important, and furfural analysis will attain a high priority.
It must be noted that the sequence of stages 1 to 4 in practice form an iterative process which we tend to call “a learning cycle”. Databases must be set-up and filled with relevant operational, maintenance and diagnostic data. Cross correlation teaches us something new every time new data is included. All the activities related to CA are depicted in Figure 2.

**Figure 2 Condition Assessment activities**

Databases are used for data-registration, planning, and the development as well as application of assessment techniques. The data may include:

- Geographic information
- Component information
- Component history
  - Operating conditions
  - Maintenance, revisions
  - Occurrences, failure
- Diagnostic data
- Assessment data

For useful analysis of failure data it is important to distinguish between equipment-parts and failure causes. The importance of dates and ages with failure data or diagnostic data is obvious, however, we only rarely observe that the age of equipment at the time of failure has been tracked. Next to operating conditions this is important in order to arrive at a correlation with diagnostic trends. The further technical CA-process is depicted in Figure 3.

The “appropriate maintenance” indication in Figure 3 results from properly selected diagnostics which can identify certain defects in specified parts. Often the condition is classified in terms of: as new, good, suspect (further diagnosis / monitoring required to investigate failure state, cause or location), bad (immediate maintenance needed). The actual maintenance need of the component further depends on the system and aspects related to the strategic condition.

**ASSESSMENT OF THE ECONOMICAL CONDITION**

The technical condition of a component is an essential part of the economical condition. Replacement, (preventive) maintenance and other strategic decisions all start with questioning the actual technical performance of the component with respect to alternative scenarios. All cost items involved in these scenarios are expressed in monetary units, summed up over a certain time interval (the Life Cycle) and converted to a Net Present Value (NPV). This exercise is called Life Cycle Costing (LCC). Whereas the remaining life (remnant lifetime) indicates the expected period of operation based on strictly technical arguments, the most cost-effective scenario is determined by LCC. Such analysis generally includes the following cost items:

- Capital investment
- Operational costs
- Maintenance costs
- Failure costs

Capital investment is the amount of money to be raised at the time of replacement, operational costs involve losses, maintenance costs involve maintenance labor, materials and diagnosis, and failure costs denote the failure rate times consequential costs. This last item includes a capital portion, labor portion and, important in a liberalized market, breach of contract, non-delivered energy, claims and loss of image. The failure rate is estimated by correlating the technical condition to failure data, as illustrated in Figure 4.
The “cost-effective maintenance” indication in Figure 4 results from evaluating two or more scenarios with different maintenance policies (Corrective-, Time-based-, Condition Based Maintenance etc). In principle this is determined by the coupling between maintenance activities and failure rates; the aim of the LCC analysis is to arrive at an optimum in the overall costs (including maintenance and failure costs).

Similarly, the optimum replacement time for equipment is a battle between increasing failure costs and decreasing capital investment costs. We arrive at an optimum in the overall costs at a certain age of the component. This age is named the “optimum replacement age” and if this age is higher than originally planned we speak of service life extension and “justified postponement of investment”.

CONDITION ASSESSMENT AND MAINTENANCE

The role of CA in maintenance programs is concluded to be twofold; on the one hand technical condition assessment states the condition regarding defects and degradation. This enables (the planning and execution of) specified maintenance. On the other hand, the economic condition states the economic consequences of this condition over a certain period of time in several scenarios with different operation, maintenance and / or investment policies. This does not only result in justified maintenance but also supports decisions related to maintenance policies, operation policies and replacement strategies.

Our experience has learned us that a utility can reduce the maintenance budget by 20-25% by implementing condition based maintenance in situations where specific maintenance is cheaper than corrective- or time based maintenance. Besides, appreciable capital expenses can be saved by justified postponement of investments for depreciated but otherwise sufficiently functioning assets. This is all in line with the trends in modern asset management which show a shift from maximum to specified performance, from avoiding to controlling risk and from “gut-feeling” decision making to “fact-based” decision making.

CONCLUSION

Condition assessment requires both diagnostics and tools for adequate interpretation, working together in a so called “learning cycle”. At KEMA we have developed systems for periodic inspection (on-line / off-line) of the most important components in power transmission and distribution networks and have integrated these into a complete condition based maintenance supporting tool, including diagnostics, interpretation, Life Cycle Costing and data management tools. KEMA has developed numerous references, norms, trends and knowledge-based rules to classify the measured data and to relate these data to practical advice ranging from direct maintenance actions for repairable defects to investment decisions and O&M policies for aged equipment.

REFERENCES


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