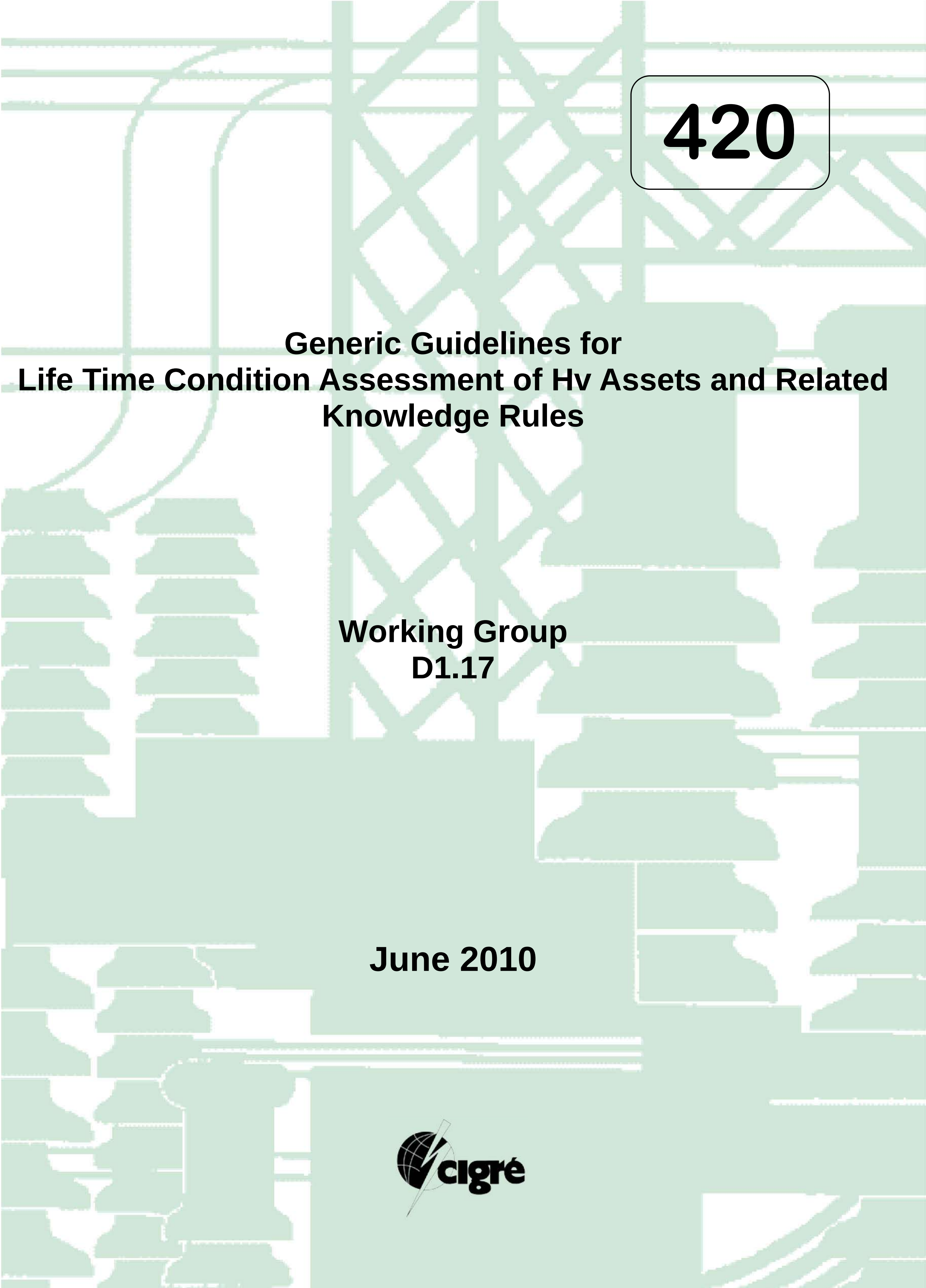

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Generic Guidelines for Life Time Condition Assessment of Hv Assets and Related Knowledge Rules

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Generic Guidelines for Life Time Condition Assessment of Hv Assets and Related Knowledge Rules

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Framework for Reliability Management of Hv Infrastructure

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Contents

1 Introduction (Executive Summary)

FRAMEWORK FOR MANAGEMENT OF HV INFRASTRUCTURE

High voltage (HV) components like cables, transformers and switchgear play an important role in the transmission and distribution of electric energy. Failures in a utility's network can lead to a loss of reputation, a financial penalty or in customers changing service providers. A well considered Asset Management (AM) strategy involving condition monitoring and maintenance is essential to maintain a high quality of supply.

Successful asset management relies heavily on the use of information and data to facilitate the decision making process. Decision making is improved if the process uses information from a variety of sources including from within the organisation, operating environment, technical groups, manufacturers, maintainers and repairers. This often results in a very complex decision making process, containing vast amounts of information that must be considered in the context of a technical, economic and societal framework. In more detail, Figure 1 shows elements of a typical AM decision making scenario.

Figure 1: Life assessment considerations for HV infrastructure.

This report describes the fundamental aspects of the AM decision making process and the information sources that are necessary for AM of HV apparatus. Covered will be guidelines for condition assessment, knowledge rules and criteria that influence the interpretation of measurement results.

The AM process should not only deal with the failure modes of specific components but also with changes in configuration as well, such as occurs when the system is augmented or repaired, for example cable repairs.

These days almost every utility has a condition monitoring program as it is seen as a tool to reduce maintenance costs and increase the reliability of the network. For example, despite breakdowns in a cable system, it can be repaired by the replacement of several metres of cable and the addition of two new joints; which is time-consuming and expensive. The outage time as a result of a breakdown can vary in different circumstances and can depend on network structure, complexity of the repair, availability of specialised labour and typically resulting in outage times from minutes to many days. Preventative maintenance actions scheduled on the basis of condition monitoring are cost effective and less time consuming than allowing equipment failures.

This report shows how to find the right information to support AM and where and how to perform maintenance on power equipment. In general, AM must address the question: What to do and when? This is often known for individual components, but there is no general approach covering the whole apparatus. In this report, generic guidelines are described on how to select the right components for maintenance and condition assessment. After this selection, the most appropriate assessment tools should be used to determine the condition of the component and if possible the remnant life. For the latter, knowledge rules are necessary, which are often based on experience combined with component expertise.

In the Chapter 2, considerations and criteria for remnant life decisions are described. The decision on where to perform the assessments is handled by failure statistics, network configuration, operation information, environmental considerations and legislation requirements. In Chapter 3, the overall AM decision process and information are discussed in relation to technical, economical and societal considerations. In addition, Chapter 4 reviews how to select the right assessment techniques and how decision making is performed.

Chapter 5 focuses on using AM data for ranking assets to highlight those that require further investigation. The techniques covered include expected service life, age, failure statistics, impact of failures, maintenance costs, qualification of components for re-use, geographic positioning and installation condition. Chapter 6 discusses the factors that influence the deterioration of the critical components. Also, the defect definitions and characteristic symptoms that identify the deterioration process are attributed to materials, design, specifications or human factors. When the deterioration mechanisms and symptoms are known, condition assessment tools can be selected or developed to detect these mechanisms and symptoms.

Chapter 7 describes the guidelines for selections of suitable condition assessment tools, alternative test voltages, conformity to measured parameters, the nature of interference and general data fidelity. In order to find the most useful data and accompanying analysis, Chapter 8 describes the handling and quality guidelines for measurements, confidence intervals, statistical analysis, methods of interpretation and data mining techniques. Finally, Chapter 9 focuses on how to transfer the collected data into appropriate maintenance actions.

2 Considerations and criteria for asset management

FAILURE STATISTICS
NETWORK CONFIGURATION
NETWORK OPERATIONS
ENVIRONMENTAL CONDITIONS
RELIABILITY AND AVAILABILITY
LEGISLATION
TECHNICAL CONDITION

2.1 Failure statistics

As no high voltage component has unlimited life, every component will demonstrate a failure behaviour. This behaviour will vary with the type of component, operating environment and maintenance history. The main goal of applying maintenance is to prevent failures. However, if certain components show an increasing number of failures then the maintenance program should be adjusted to focus on these failing components. This often requires the combination and consideration of large amounts of practice and failure data and its conversion into actionable tasks within a maintenance program.

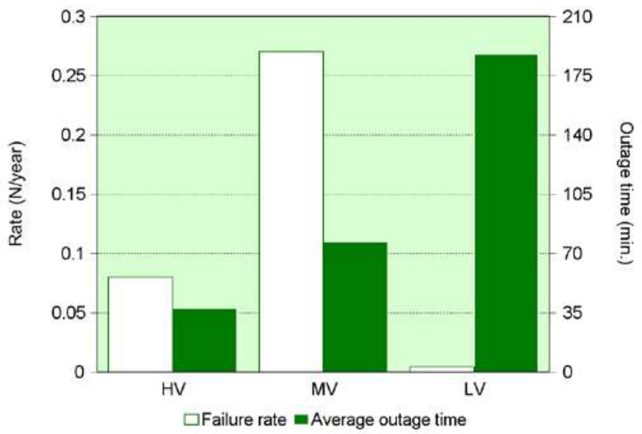


Figure 2: HV, MV and LV network failure rates and average outage times per interruption of electricity customers in the Netherlands. The values are averaged over ten years [7].

In particular, the failure information of a particular network has to be considered using as large a population as possible e.g. within the database used for decision support, see Figure 2.

2.2 Network configuration

The construction, operating environment and operational history of HV assets are important considerations for reliable condition assessment. If it is to be effective then all of the relevant elements have to be identified. For example, in the case of a distribution power cable used to inter-connect small substations, the cable sections may consist of three different types of components (Figure 3). For practical reasons, a cable may be constructed from multiple elements which are connected to each other with cable joints. At both ends of the cable there is a termination to enable the connection to a HV installation. Due to repairs or changes in topology, cable sections often consist of various types of joints, cable types, accessories and terminations of various ages. Moreover, the different topological and operational conditions of a particular cable system strongly influence the service life. When assessing insulation condition of power cables in a network, all of these elements need to be appropriately combined to generate knowledge to support decision making, see table 1.

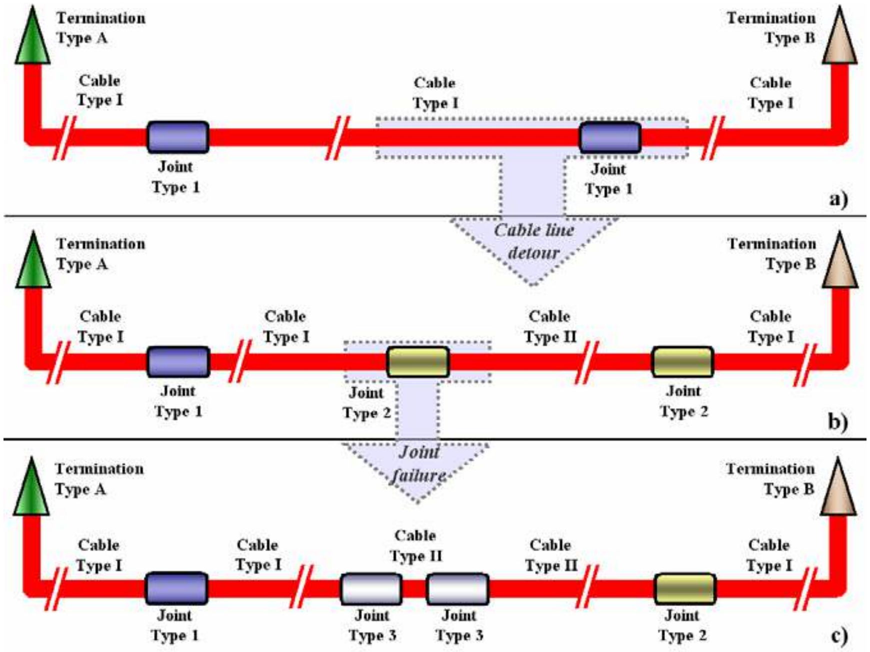


Figure 3: Construction of a cable-section from different types of components, the age of components as well as the maintenance history may vary.

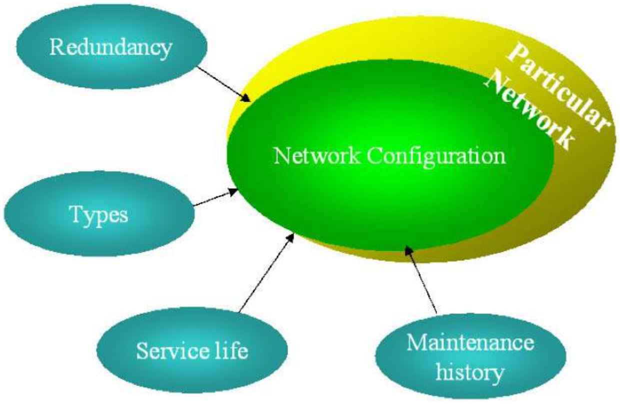


Figure 4: Important configuration elements of a network.

The context for decision making in networks is shown in Figure 4. The data pertaining to these elements is often found in a number of databases which, in a large system, can be overwhelming if considered without the use of decision support software tools.

Table 1: Database knowledge domains for power cables	
Component domain	consisting of specific insulation characteristics of the cable structure; e.g. cable insulation and accessories
Diagnostic domain	consisting of the type of diagnostics applied; e.g. general condition assessment or assessment of weak spots
Measuring data domain	defining specific diagnostic quantities used during condition assessment

2.3 Network operation

During the service life of HV components the operational needs of the network will result in changing profiles of electrical, thermal and mechanical stresses, Figure 5. In particular, a number of elements are of importance in evaluating the potential loss of service life, such as:

- the load history and the forecast annual load
- maintenance issues: poor workmanship, spares availability and substitution, digging activities
- type faults in equipment increasing the vulnerability of equipment to service conditions
- short-circuit history

Due to the fact that there is a direct relationship between insulation degradation and thermal load, knowledge of loading parameters is important for estimation of loss of life. In the case of power cables, changes in thermal load may influence axial and radial expansion and thus result in additional degradation effects, e.g. local field enhancement, gas formation or treeing

2.4 Environmental Conditions

Environmental conditions may also play a role in the degradation processes, in particular,

- ground water level and pollution,
- weather /climate,
- mechanical stresses, and
- stray currents

are all important parameters and they have to be separately evaluated for particular networks.

Statistical analysis has shown that there is a relationship between the ground moisture content and insulation degradation of power cables. Cable installations may also suffer from localised heating resulting from drying out of surrounding soils in response to climatic conditions, nearby earthworks or issues associated with backfill material properties. Stray currents from neighbourhood railway lines may cause corrosion of connections and metallic protective elements of the cable sheath resulting in accelerated degradation.

2.5 Reliability and Availability

The drive to maximise economic returns from the power network and the requirement for continuous availability of supply, have made it increasing difficult to schedule maintenance activities. Plants with continuous processes can often only maintain their assets when there is a planned outage. Forced outages often do not represent a cost effective or convenient opportunity for maintenance. For industry, prolonged loss of supply can result in process related damage to the plant or loss of product, with severe economic impacts to a business. Therefore there is a need to consider maintenance activity in relation both technical and economic impacts.

As an example, in the case of a power cable network the required reliability and availability is strongly influenced by what is deemed as an acceptable risk. This is graphically shown in Figure 5, where the failure probability versus the failure consequence, giving the risk, is shown. Finding a component with a low reliability in a critical circuit will necessitate a maintenance action that will improve the reliability dramatically. From a risk perspective, a component with a very high reliability in a non-critical circuit represents an opportunity to decrease maintenance activities.

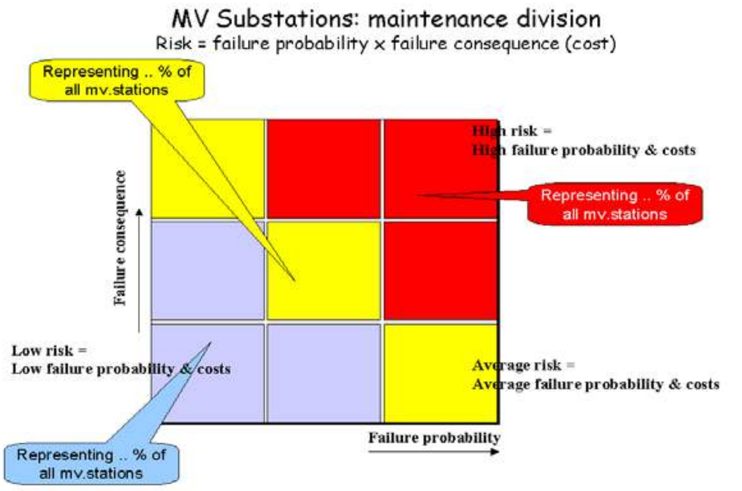


Figure 5: Practical example of prioritising maintenance. Applied practice in a distribution network [2].

An example from one utility company is based on estimating the consequences of failures in a network with the following categories,

1. Number of connections involved, e.g. < 200, 200-800 or > 800,
2. Customer type, e.g. small industry, large industry or household,
3. Expected power supply interruption, e.g. 2hrs, 2hr-4hrs, > 4hrs,

and the failure probability given by

1. Asset construction, e.g. number of accessories, diameter, length,
2. Number of short-circuits, e.g., 0, 1, 2 or more,
3. Insulation condition, e.g., good, moderate or bad,
4. Operational load, e.g. < 70%, 70%-100% or > 100%.

The failure probability is estimated by the utility based on elements of risk such as age, environmental conditions and different weight factors for specific types of components. The utility even goes one step further: the total asset group is divided into three categories: critical, medium and non-critical, each with its own percentage of the total population (see Figure 5). The high risk consequence group is then submitted to the normal maintenance program, which can consist of inspections or preventive maintenance, while for the other two groups only a representative sample is maintained.

2.6 Legislation

In many countries these days the regular inspection of the electrical assets is legally mandated in order to reduce the likelihood of catastrophic failures. For example, in the Netherlands (NEN 3140) the inspection intervals of plant can be determined on,

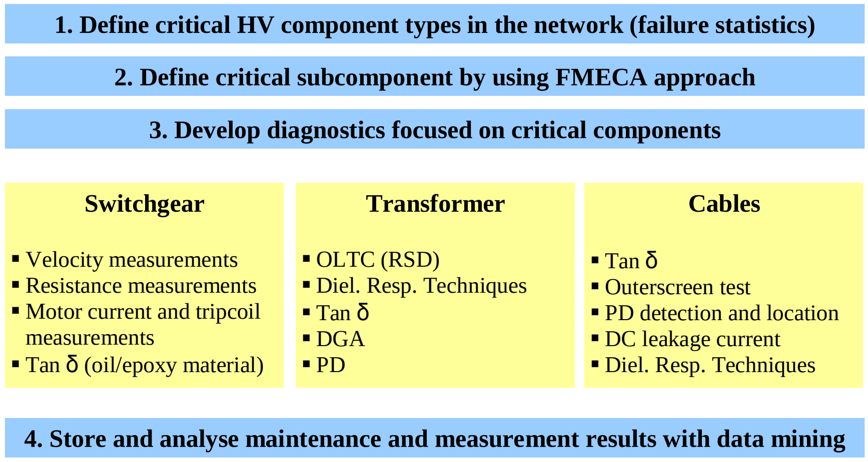
- Manufacturer's advice
- Inspection conclusions
- Usage of the equipment
- Effects of outages

Legally the network owner needs to be able to demonstrate that the electrical equipment is in a safe condition. In response to this, inspection intervals have changed from typically every 5 years to a condition based system. Moreover, with regard to safety and environmental impacts the regulatory requirements are becoming stronger with time. In particular, NEN 50110-1:2005 (Netherlands) recommends that the responsible service provider has the obligation to collect in a systematic way the information about the overall condition of the infrastructure.

As a second example, according to Finnish law a network owner has to monitor the condition and safety of the electrical system. There must be a maintenance plan aimed at maintaining electrical safety, with regular inspections of electrical plant within five year intervals.

2.7 Condition Assessment

A manufacturer's maintenance advice is mostly based on the expected asset life. This treats all assets within a class as equal and with the same probability of failure over time. As a result, allowing for high safety margins, a time-based maintenance approach is recommended. But similar assets can age in different ways and at different rates due to the nature of their insulating materials, defect induced degradation and service environment. These variations can be exploited to economic benefit by treating assets differentially according to their condition and not their age. If you make no measurements of condition then all failures may appear as random and unpredictable. This is typically the basis of condition assessment when only population failure rates are considered.



1. Define critical HV component types in the network (failure statistics)

2. Define critical subcomponent by using FMECA approach

3. Develop diagnostics focused on critical components

Switchgear	**Transformer**	**Cables**
▪ Velocity measurements ▪ Resistance measurements ▪ Motor current and tripcoil measurements ▪ Tan δ (oil/epoxy material)	▪ OLTC (RSD) ▪ Diel. Resp. Techniques ▪ Tan δ ▪ DGA ▪ PD	▪ Tan δ ▪ Outerscreen test ▪ PD detection and location ▪ DC leakage current ▪ Diel. Resp. Techniques

4. Store and analyse maintenance and measurement results with data mining

Figure 6: General approach of condition assessment. From a Failure Mode Effect and Criticality Analysis (FMECA) the types of defects are analysed, for which the different diagnostics can be develop and applied. In the shown figure, some examples of diagnostics are given: *dissipation factor (tan δ), isothermal relaxation current (IRC),* ***dissolved gas analysis (DGA), power factor (PF), partial discharge (PD), On-Load Tapchanger Diagnostics (OLTD).***

There is scope for considerable improvement in decision making if condition information forms the basis of assessment.

The major elements of a considered maintenance program should be based on the component type and its present insulation condition. To monitor the changes in an asset or its particular components, suitable diagnostics are necessary, Figure 6. For power cables, electrically based diagnostics are the most convenient. Diagnostic procedures for monitoring cables during service are generally non-destructive, whilst some out of service tests may result in a small increase in aging of the insulation system under test. This small loss of insulation life though is acceptable within the context of improved asset management.

In non-destructive diagnostics, the stress has no measurable effect on aging. Typical examples are dielectric response methods and partial discharge measurements when applied at voltages not higher than operational stresses, these can provide valuable information about insulation degradation [19, 20].

Destructive testing techniques are those that have the potential to cause failure of the insulation if it is weak. Even if no failure occurs then it may result in a small loss of insulation life.
Therefore from the point of view of asset insulation quality and reliability, four aspects are important for on-site AC over-voltage tests and results evaluation.

- A healthy (defect-free and/or non-aged) insulation can withstand for a short duration a high level of voltage stress. Whilst insulation which is aged and/or consists of insulation defects should have a lower level of test voltage.
- An over-voltage test shall be designed in such a way that the service life consumption due to a test on healthy insulation is negligible, whereas the impact on defective insulation is high enough to cause a breakdown.
- As a result of stresses associated with test voltages of levels higher than the operational stresses, the test may be destructive even if no failure has occurred.
- Due to the fact that the duration of the over-voltage is arbitrarily selected e.g. 10 minutes it can not be excluded that after 11 minutes a failure will occur.

This last point essentially warns that tests are not guarantees of condition or serviceability, but only indicators. It also needs to be understood that the term operational stresses is not the normal power frequency operational stress but includes switching surges and other over-voltage conditions to which the plant may be exposed. This is the fundamental reason that test voltages in standards are in excess of the rated power frequency continuous level.

Which condition assessment tools should be applied, or which combination of tools is dependent on the nature of a particular asset and its aging properties, see Figure 6. For XLPE cables the degradation typically results from water trees and free water in the conductor core or cable joints. This can be detected with dielectric response methods (such as PDC/FDS) and can also be applied to moisture in PILC cables. For voids in XLPE though partial discharge methods (PD) are more appropriate.

In Figures 7 and 8 is shown a utility's application of condition assessment codes for power cables. Based on diagnostic measurements a particular cable section can be categorized into 3 groups:

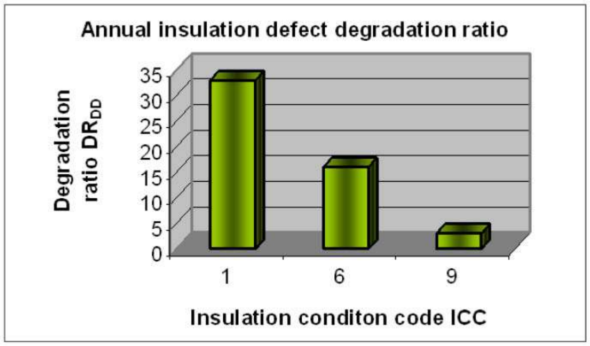


Figure 7: Annual insulation degradation ratio as determined for three different insulation condition categories

Category 9; the insulation condition code ICC = 9 means that the component is in good condition and the next inspection is scheduled in 5 years.

Category 6; the insulation condition code ICC = 6 means that the component is aged and the next inspection is scheduled in 3 years.

Category 1; the insulation condition code ICC = 1 means that the cable section is in bad condition and needs maintenance e.g. a weak spot in the cable section that should be replaced.

The information about the actual condition status is of importance for the estimation of the insulation degradation ratio e.g. annual insulation defect degradation ratio based on load, DR_{DD}, see Figure 9. Moreover, this information can be combined with operational conditions and the degradation ratio into a function of thermal aging DR_{OL}, see Figure 10. The technical remaining life curve is poor ($DR_{DD}(1)$ line) compared to the good condition of the $DR_{DD}(9)$ line. Compared to the power plant condition the operational load (within limits) has a less severe effect on the degradation process, hence the less steep descent of the curves.

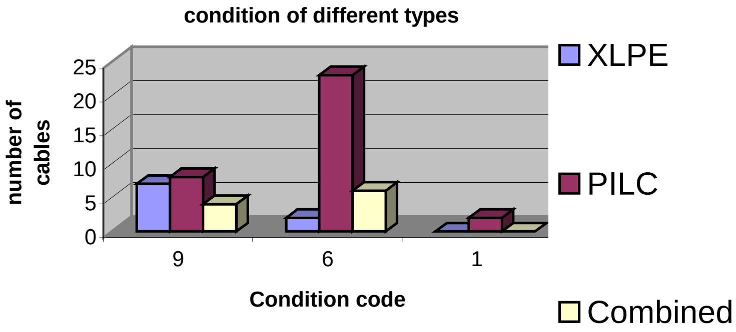


Figure 8: Example of condition assessment; based on the actual insulation condition categories of power cables in a particular network.

Combining both degradation ratios (DR_{DD} and DR_{OL}) results in the assessment of remnant life RL_{tot}. In using RL_{tot} the influence of actual condition and the operational condition are combined to indicate the expected remnant life of an asset. Based on this information for particular HV components, an effective maintenance strategy can be determined.

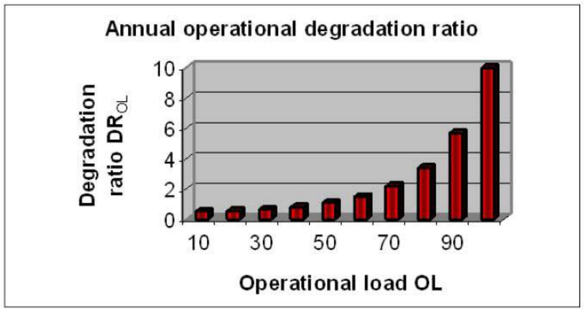


Figure 9: Annual operational load degradation ratio as determined for paper/oil insulation.

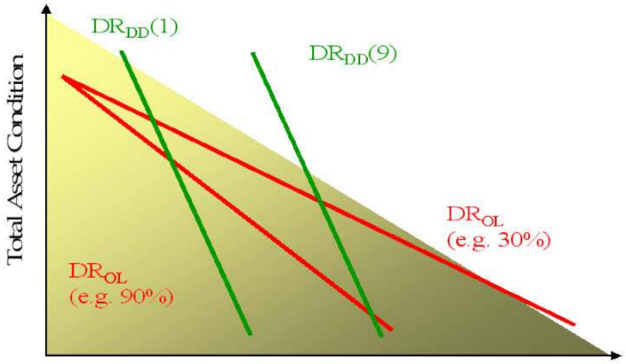


Figure 10:Example of a schematic presentation of influences of operational and degradation effects on asset service life.

3 Asset management decision process

ASSET MANAGEMENT (AM) INFORMATION
TECHNICAL FACTORS
ECONOMIC FACTORS
SOCIETAL FACTORS
OVERALL DECISION PROCESS

3.1 AM Information

For a successful asset management (AM) decision process, it is necessary to combine data from many different sources [22]. In broad terms these sources can be divided into three categories such as is shown in Figure 11. From the point of view of an organisation, most information about technical aspects might be easily available and gathered amongst (service) engineers, while the economic data will be reside with a financial group. At a corporate level there will also be an input from legal, risk management, network planning and stakeholders. When the AM decision process is supported with automated tools, all these inputs will still be necessary to arrive at an acceptable decision.

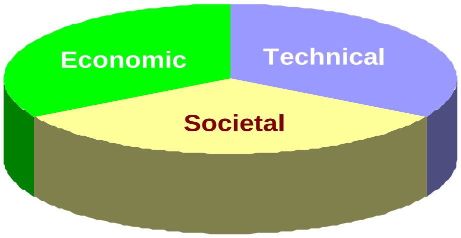


Figure 11: The three factors involved in AM decisions

This illustrates that comprehensive AM requires a multidisciplinary approach.

3.2 Technical Factors

Relevant information needed for AM decision support is dependent on several asset-related parameters, such as insulation aging of components and the probability of an over-voltage across a component, e.g. as a result of switching activities. The aging of a component may be related to the absolute age, the type, the history and the operating conditions of a network (sub) component. In order to decrease the probability of in-service failure, condition assessment can be used. A combination of diagnostic tools for condition assessment is chosen and applied, depending on the different types and locations of defects. The technical aspects cover amongst others condition assessment, aging models, and failure probability, but also information on the equipment inventory, the network topology, available spare parts, current maintenance procedures, history of maintenance actions and the history of failures.

3.3 Economic Factors

Every technical factor will have its financial counterpart; economic factors not only include the costs of maintenance, repairs and failures, but also the costs of condition assessment and the capital cost for the equipment and spare parts. In this context these costs will be called the economic information on assets. The costs related to a failure are dependent on the outage related expenditure. Failures mostly result in major damage to network components and their environment, which will lead to high maintenance and repair costs. In the case of major critical plant, provisional solutions are needed to restore supply as quickly as possible, eventuating in higher expenditures. Outages can also result in lost revenue due to undelivered energy, in compensation to customers and penalties from regulators. These elements will be called the economic information on business.

3.4 Societal Factors

Technical and economic factors are not the only considerations, as an example, risks are not only determined by economic factors. There are also some societal aspects that have to be considered, such as the impact on society of outages and failures. Failure acceptability can be considered as the degree in which a failure is acceptable from a social point of view. The failure impact depends on the criticality and number of connections affected by a failure and the time to restore supply. Even so, frequent energy interruptions in a short period of time will not be acceptable from a social point of view. Furthermore, the social impact of a utility’s policy considers factors such as the public image of the utility and their feeling of safety. For example, the general public has little tolerance for power losses to buildings with a high social standing such as hospitals.

Some of the societal factors will be mandated by the regulator, which will translate these requirements into regulations. These regulations will then result in economic impacts such as penalty costs. Other societal factors such as the image of the power utility or the personal safety of its employees cannot be easy translated into economic considerations, but should also be covered in considering risk.

If AM is being carried out without consideration of all of these factors then a seemingly good, low cost technically based AM plan can readily result in significant costs from societal and economic factors such as loss of supply resulting in regulator actions (penalties or restrictions) and loss of customers.

3.5 Overall decision process

When pursuing optimal economic performance, decisions have to be made about which of all the possible maintenance or investment actions is best. Simply put, this can be seen as a decision process, where decisions are made based on technical, economic and societal information. However, this is a continuous process, as decisions influence the system, and therefore influences at least the technical and economic information on which the decision is based. To avoid complexity this recursive aspect of the decision process is not reflected in the figures.

In more detail, this decision process can be seen as build of three separate levels, as illustrated in Figure 12. The first level deals with the technical information; the second level uses the results of the first level and the economic information on assets, while the third level combines this with the economic information on business and societal information.

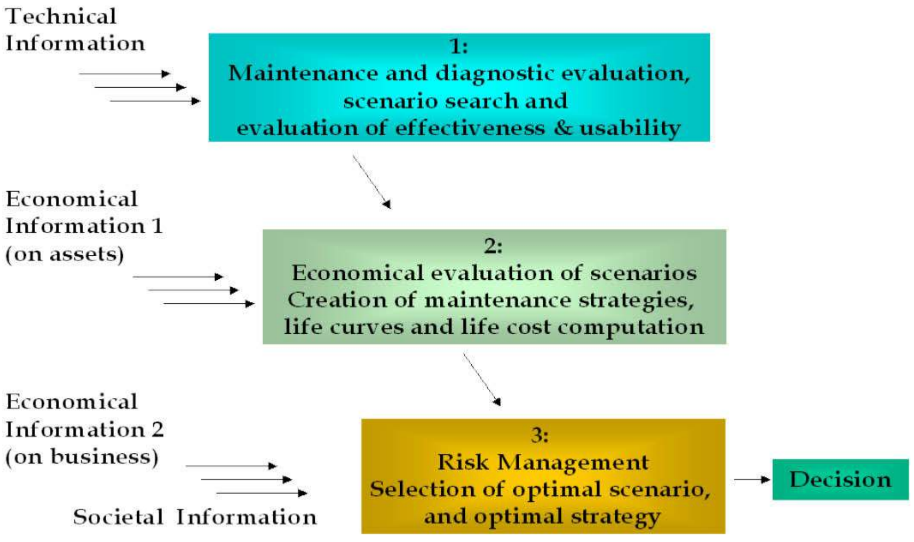


Figure 12: Asset maintenance management decision process on three levels [22]

A way to approach this separation is to think of the first level, which consists of technical information and is mainly focussed on components, as the component level. The second level, which combines the economic information on assets with the results of the first level, has more focus on the level of the network (the reliability and operational performance), while the third level uses the economic information on business combined with the societal information, to make decisions about risk which has mainly a corporate focus.

From a technical point of view, there are many variables that can be incorporated into an AM strategy but each has a different impact on asset performance. For example there are strategies based on increasing or decreasing maintenance, changing inspection intervals, replacement or refurbishment, using corrective, time based or condition based maintenance. The appropriate strategy evolves from an analysis of equipment inventory, maintenance actions already performed on the equipment, current maintenance guidelines, condition assessment, results from diagnostics, statistical evaluation of failures, reliability and aging models.

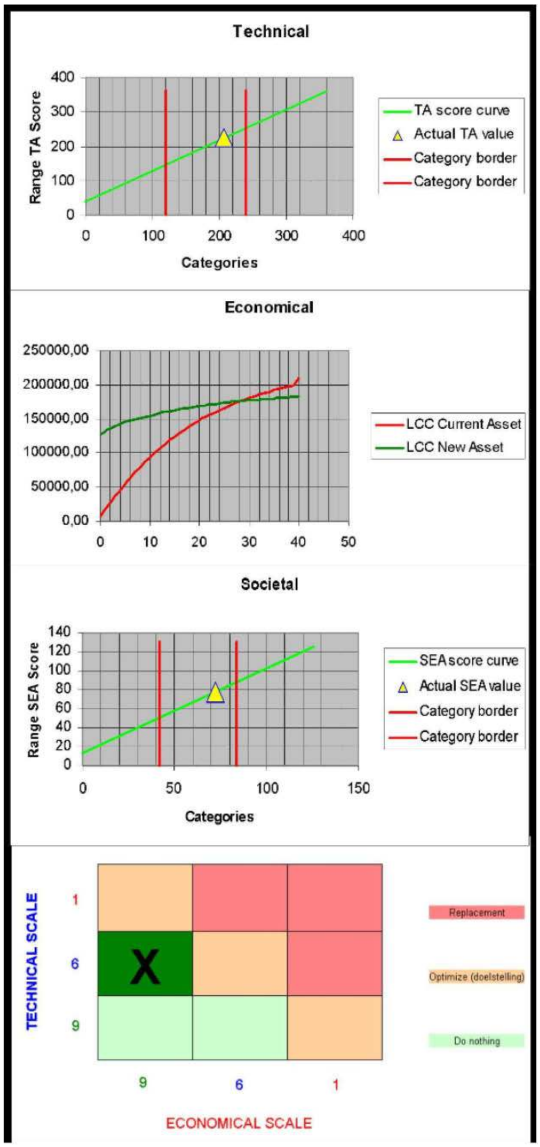


Figure 13: Example of output from a decision support tool addressing the three categories of information, technical (technical assessment TA), economic and societal (societal economic assessment, SEA) and Life Cycle Cost (LCC).

All these factors will have a different effect on the technical performance of the asset, in terms of its reliability and availability. At the early stages, scenarios should not be excluded based on their effect on technical performance. At the next stage these scenarios are combined with other relevant results to produce a compound result. The stakeholder's expectations for example will be taken into account at the third level.

A combination of the technical information with relevant economic data will result in a quantification of benefits and costs for each scenario. These benefits and costs are not exclusively expressed in economic terms, but could also be in terms of reliability or expected asset life. For example, enlarging an inspection interval may result in the benefit of decreased maintenance expenditure, but could have costs in terms of decreased reliability. Conversely, shortening the inspection interval might result in increased expenditures, but could lead to increased reliability.

As this process is highly non-linear it is not uncommon to find negative consequences in some areas producing a net benefit to the organisation. Thus it is possible that scenarios will emerge with negative impacts on technical performance that result in an overall reduction in economic and societal risk.

Useful decision support tools should address all the categories of information at different stages in the decision process. The tool should support the asset manager's decision process and be easy to use. This will encourage the use of the tool and the quality of asset management decisions will improve. Figure 13 shows the output of a decision support tool using the discussed categories of data.

When an AM strategy is implemented without proper reference to technical, economic and societal considerations then it will generally not lead to an efficient outcome.

4 Selection of decision assessment types

MANAGING THE AGING PROCESSES OF HV ASSETS, AS FORMULATED BY CIGRE WG D1.11

4.1 Aging Management

Obtaining the full economic life from assets is challenging, particularly when it is carried out in the absence of complete knowledge of the aging process and its indicators. This is made more difficult when equipment is old and the links with the original manufacturer and even the original technical information and maintenance instructions are lost. This lack of timely and comprehensive information undermines the ability of asset managers to make informed decisions.

The aging of an electrical asset will typically be indicated by the degradation of key components. Where these are mechanical or involve fluid replacement, they can usually be effectively managed. The electrical insulation is more difficult to manage as electrical insulation elements also play a structural role within the asset; their aging process, influences and indicators are less well understood. A major reason is the lack of a coherent analytical methodology which is supported by a database of case studies.

A further complication has been a discontinuity between two traditional approaches to the analysis and diagnosis of aging insulation; the first is based on accelerated aging studies in the laboratory, which cannot duplicate multi-factor aging. The second is the relatively unstructured approach of the utility investigator, based on ad hoc analysis of failed in-service equipment subjected to multi-factor aging conditions. However, by examination of the processes involved in the two approaches an underlying analytical structure based on forensic evidence from the failure and knowledge of the dominant failure modes, can be espoused.

CIGRE Task Force D1.11.01, of Working Group D1.11, ‘Service Aged Materials’, has bridged the gaps and incorporated a feedback process by which the service aging of high voltage equipment can be better anticipated and the incidence of disruptive failure reduced [7,8]. A methodology has thus been developed to link forensic evidence from failed plant with the theoretical failure modes observed from laboratory studies. The process developed merges the underlying analytical structure of both approaches. Using this methodology, a range of practical options can be structured for the better management of aging plant.

The developed methodology utilizes the knowledge base of failed or near failed components and firstly establishes their dominant failure modes. After the dominant failure modes have been established these are correlated with the associated forensic evidence in the early, advanced or late stages of insulation degradation. This is to assist practitioners in developing a preventative maintenance strategy as soon as possible.

For a forensic study to give a complete picture, diagnostic information should be available at every stage of the insulation’s life. However such information is rarely available and this can limit the forensic data to that obtained from examination of units with major damage or units whose failure is imminent. As much information as possible is obtained from previously applied diagnostics and from any tests on similar equipment. The challenge is then to work back from what evidence is available using information on the aging mechanisms that lead to the assessed failure mode (this can be from laboratory studies or detailed monitoring of a specific item of equipment of the same type).

It is recommended to establish for each equipment class a good database of information on aging equipment. While failed equipment will always be thoroughly investigated, this may not always be done with an eye to better understanding of the aging process. Useful information on the aging processes during the full service life includes loading, maintenance test results, general ambient and environmental conditions and details of any site moves. This may be enhanced by using data mining techniques to display trends which may not be apparent from normal diagnostic analysis methods.

4.2 Description of methodology

With reference to Figure 14,

(i) The first stage is the identification of the **dominant failure modes** of the key insulation components, eg, HV cable joints and terminations, generator stator bars or the layered oil impregnated paper insulation of high voltage instrument transformers. This is available from the knowledge base of experts, who may be researchers, manufacturers, maintainers or utility engineers. It is not necessary to identify all possible failure modes for a successful failure mitigation strategy to be devised.

In the case of high voltage instrument transformer oil impregnated paper (OIP) insulation, for example, there are two dominant failure modes; thermal instability of the oil/paper dielectric and dielectric overstressing with partial discharge activity. For generator stator bars there are three dominant modes; inter-turn short circuits, reduction in ground wall insulation thickness/electrical puncture and end-winding discharge/electrical tracking.

(ii) The next stage in the process is to identify and **correlate the principal forensic evidence** with each failure mode. Effort should be made to categorize the forensic evidence into early, advanced and late stages of activity. This is to enable early identification and prompt action to be implemented on the most vulnerable units.

(iii) The insulation aging processes are next defined and detailed for each dominant failure mode and the time frames estimated from fault inception to disruptive failure. Knowledge of the fault propagation time frames should enable an informed decision between options of periodic diagnostic testing, continuous monitoring or immediate replacement.

(iv) With knowledge of the aging processes for each failure mode, the **key influencing factors** can also be short listed with their **levels of significance**. These influencing factors which drive the accelerated aging process may be **internal** (e.g. related to design, manufacture or installation) or **external** (e.g. related to environmental influences such as moisture ingress or transient over-voltages).

(v) With knowledge of the forgoing, the most relevant testing or diagnostic techniques are then listed. These are categorized in terms of their sensitivity to the degradation processes associated with each failure mode.

(vi) The final step in the methodology is to gather together the outputs from this process into a **management strategy** which can be used for; (a) preventative maintenance for the class of equipment, (b) decisions on equipment change-out and (c) improvement in the specification, design or manufacture of new equipment.

Even if all the elements shown in the structure are not completed, there are advantages in using the approach to the analyst. Firstly, a universal ‘template’ exists for the structured analysis of a failure and its broader implications. This is important nowadays due to the diverse responsibilities of asset managers and their increasing time constraints. Secondly, if a data bank of typical case studies is built up (as commenced in [6]) aspects such as the most sensitive diagnostic for a particular failure mode and the most likely fault propagation time for that mode can be referenced, greatly increasing the efficiency of the degradation management process.

To effectively manage the aging processes of HV assets, it is considered necessary to have a structured methodology to analyse and prevent in-service failures, preferably with a databank of case studies for support. In the past, there has been a reserve of knowledge that has been available in utilities or universities for the analysis and management of aging insulation. Nowadays such skilled knowledge is becoming less accessible.

CIGRE Task Force D1.11.01 [6] has developed a databank of reference case studies for the following plant;

(i) HV instrument transformer insulation
(ii) Rotating machine stator winding insulation
(iii) XLPE cable joints and terminations
(iv) Transformer pressboard insulation

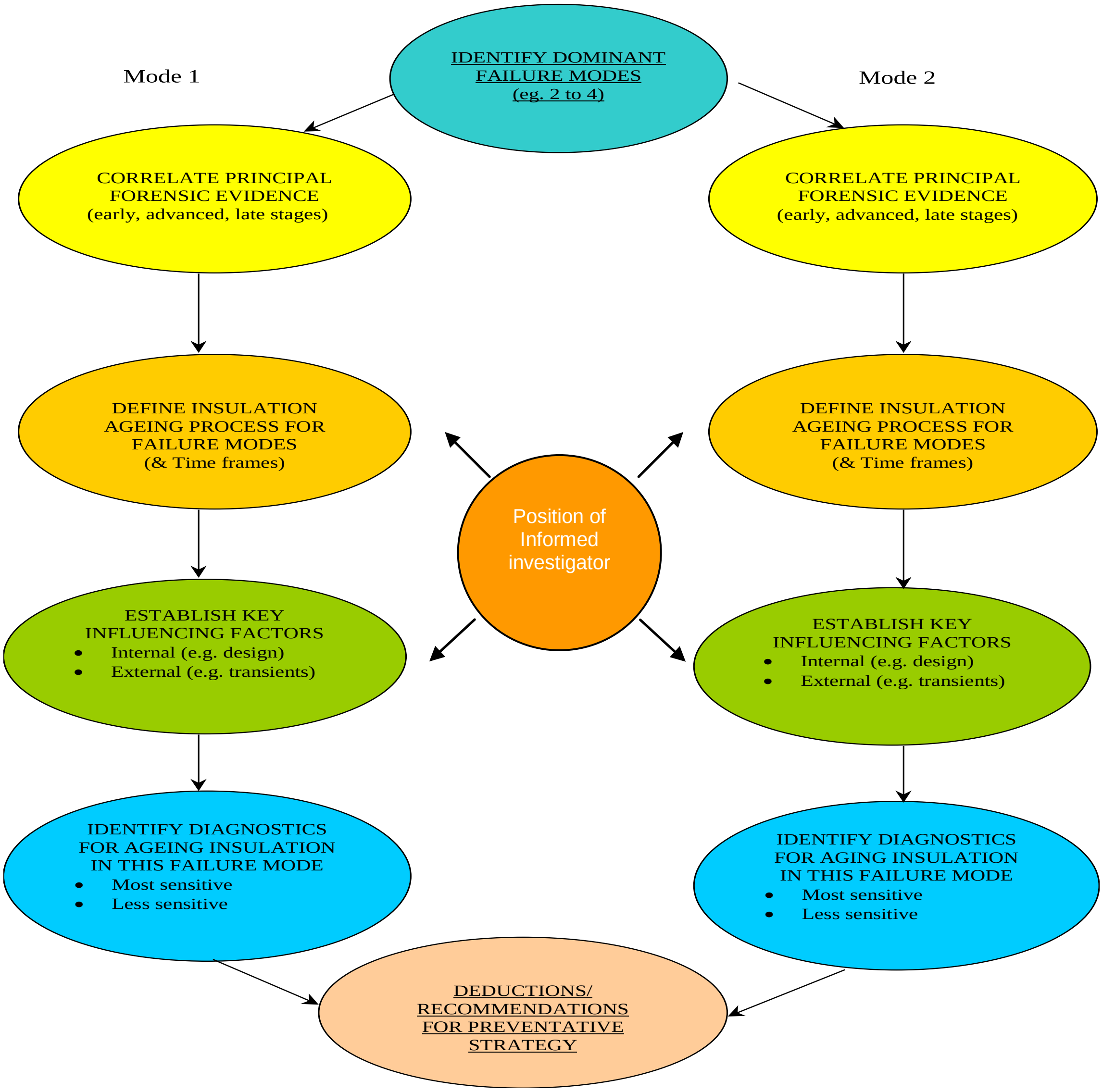


Figure 14: Illustration of the strategic position of an asset maintenance manager using the proposed methodology for aging plant failures [5]

The implications of the methodology in managing the aging process of HV insulation are given in the table below.

Methodology for Service Aged Asset Management

Stages in Methodology (Progressive)	Associates Sub-Stages in Methodology	Implications for a Management Strategy
Identify dominant failures modes	(Two or three modes are usually prominent)	Higher level check on equipment vulnerability
Correlate principal forensic evidence	Categorize as early, advanced and late stages of activity	Enables prompt identification of problem and action necessary on most vulnerable units
Define insulation aging processes for failure modes	Also estimate time frames from fault inception to disruptive failure	Enables informed decision on either periodic testing, continuous monitoring or immediate replacement
Establish key influencing factors	Categorize as internal (eg. design) or external (eg moisture ingress). Estimate levels of significance	Effective steps can be taken to isolate and address cause of insulation degradation
List most relevant diagnostic techniques	Categorize as ‘most sensitive’ and ‘less sensitive’	Enables choice of diagnostic techniques most sensitive to leading indicators of insulation degradation.
Recommend maintenance or replacement strategy	(Determine relevance for similar classes of equipment not yet failed)	Informed and effective failure mitigation and maintenance strategy for equipment classes in question.

5 Criteria for condition assessment

Failure Patterns
Age & Expected Asset Life
Current Maintenance Costs
Impact of Failures
Restructuring the Network
Geographic Positioning (city/rural)
Installation Condition (direct buried, wet grounds etc)

Due to the numerous types of HV components it is impossible to implement condition assessments for the whole population at once. In order to select HV equipment which would benefit from condition assessment, it is necessary to apply varied selection criteria. The criteria described in this chapter support this selection from a system point of view.

5.1 Failure patterns

Failure rates in the network are an important indicator for selecting a network for condition assessment. These can be analysed on two different levels:

1. **Network level**:
   Failure patterns at the network level give information about failures which are typical for specific areas or type of plant (Figure 15). For example an increased amount of failures of cables in a certain area with a high level of ground water can be a reason to apply condition assessments in this specific area.

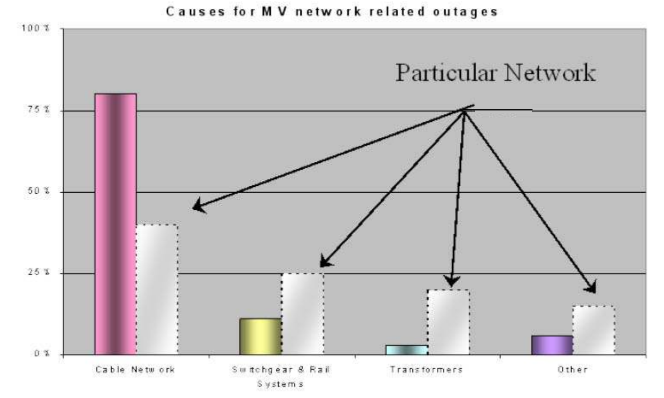


Figure 15: Failure analyse of two networks.

2. **Component level:**
   Failure patterns at component level are more related to a particular component and subcomponent type like joints, insulating oil or tap changers. Depending on the type of component, manufacturer or year of construction, the deterioration behaviour can be different. The failure pattern at the subcomponent level can also be influenced by the failure pattern at the component level.

   Components with increased failure rates should be the focus of condition assessments. These increases in rates can often be the result of overall aging of the component or due to specific deterioration in one of its subcomponents.

A combination of network, component and subcomponent level analysis will result in the best selection criteria for HV equipment which is most appropriate for the application of condition assessment.

5.2 Equipment Age and Expected Service Life

The age and expected service life of equipment is a strong influence on the use of condition assessment. Older components are the most common subjected to condition assessment in order to determine the optimal time for reinvestment. Figure 16 shows the transformer age distribution of a relatively young MV power network.

However, just relying on the nameplate or install age of HV equipment can be very misleading. For example, due to the local changes in topology through maintenance or augmentation, a cable system will end up comprising of joints, terminations and cable accessories of various ages, manufacturers, materials and states of deterioration. Thus different and unexpected degradation mechanisms can exist at the same time within the system. For transformers the same could be said about insulating oil, tap changers or bushings.

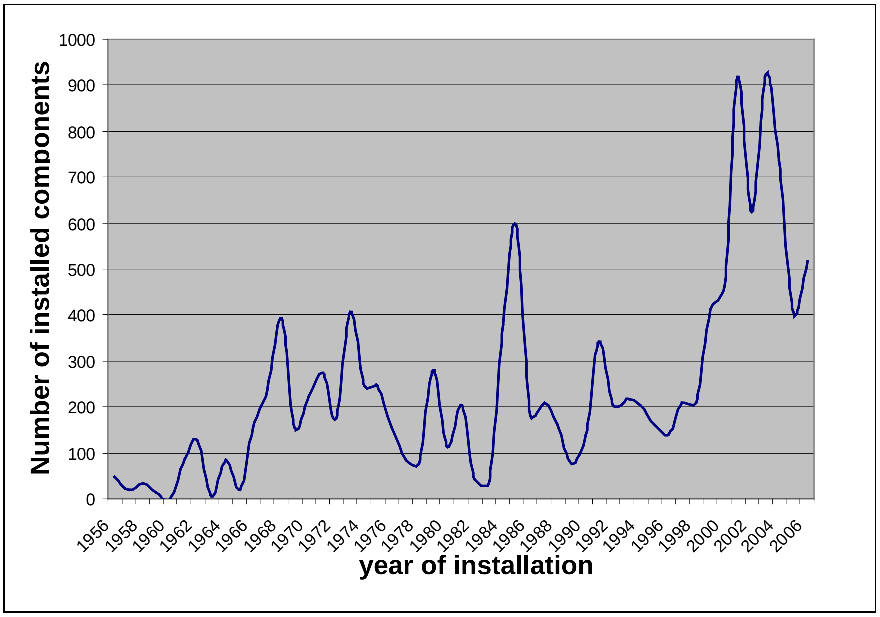


Figure 16: Example of the age distribution of distribution power transformer in a relative young MV network.

5.3 Impact of failures

Taking a cable system as an example, the outage costs have both direct and indirect components. The direct costs are typically the repair or replacement costs (component level). The indirect costs are penalties and the loss of supplied energy (system level cost) [1].

The costs of one failure (***Cfailure)*** can be calculated by summing the costs of non delivered energy, the costs of claims and penalties (***Ccp)*** and the direct costs for repair of the disturbed component (***Cr***). The cost for non delivered energy (Cnde) is related to the duration of the power interruption.

$$C_{failure} = C_{nde} + C_{cp} + C_{r} \tag{5.1}$$

The duration is influenced by both the systems topology and the time that is needed to recover the energy supply.

The indicative penalties for non-delivered energy are dependent on the different types of connection to the power network. The standard penalties are different per country, determined by the government or through contract. Several examples: e.g. Finnish government has set the following penalty. A company has to pay a customer from 10% to 100% of customer's annual network service fee. The amount depends on how long the outage lasted beyond 12 hours. Maximum penalty is €700 per customer. E.g. in the Netherlands, the penalties are dependent on the connection type and are applicable after 4 hours, with households ($U < 1kV$) € 35, small industry ($1kV \leq U < 25kV$) € 900 and large industry ($U \geq 25kV$) € 90.000. Furthermore, liability claims can in most countries be submitted in case of disturbances, where the indicative compensations are for industries €10 per non-delivered kWh and for households €1 per non-delivered kWh.

The direct repair costs not only depend on the costs of the material used but also the elapsed time before the repair can be started. For example in case of duct or conduit based systems many utilities have safety procedures to apply before approaching active power lines or it often occurs that in practice you have to remove water from manholes and ducts before repairing a line, which is also costly. Also, the time that is needed to locate the fault can vary from minutes to weeks.

Apart from economic considerations, there are many other influences on the decision criteria for determining the correct approach. These may include the need or desire to improve safety for personnel and the general public, or to reduce possible environmental damage. As an example, a utility increased the measurement frequency for certain current transformers which had an increased probability of catastrophic failure. In this case for a public utility, the relationship between the costs of the increased measurement program was not difficult to justify in comparison to possible costs and impacts of the loss of life. Often the cost of a repair can seem large until they are compared to the cost of the consequences of not performing the repair. In this context compare the cost of taking a transformer out of service for a bushing repair rather than letting it fail explosively in service because the condition was undiagnosed.

5.4 Current maintenance costs

Current maintenance costs are influenced by HV component aging and failure rates. Maintenance costs contain costs for preparation (switching etc), inspection (visual or by measurements) and maintenance actions. Also, the population size should be taken into account in determining the total costs for a maintenance program. A small population of very complex components with high maintenance and investment costs can be equally attractive for remnant life and condition assessments as is a larger population of more simple components. The criteria described in this section should be used for both defining the ranking of the HV equipment in the priority list for Condition Based Maintenance (CBM) and to support the cost benefit analysis.

Maintenance costs are incurred from many varied sources, with some easier to quantify than others. Consider,
- labor - cost related to the internal or external staff involved in the maintenance activities
- tools - costs related to tools and equipment that the staff are supplied with
- measuring equipment – cost of the specific measuring equipment
- spare parts – availability and usage of spare part for maintenance purposes
- reserve capacity – costs related to the extra capacity needed for the availability of the HV equipment

Dependent on the HV equipment involved, less or more of these costs are involved.

5.5 Qualification of components for re-use

Due to the capital cost of components and these days the increasing desire to reuse components on environmental grounds, a question can conceivably arise such as for a cable system, “Is the current cable in a good enough condition to reuse for some other role within the network? Such a question is relevant grounds for the application of condition assessment to the cable system.

As an example, most of the installed PILC cables are at the end of their original design life. A complete replacement of these cables would require an enormous investment. A possible solution is that cables with the worst condition could be maintained or taken out of service. Also, changes to the load profile could be used to avoid premature or unexpected failure.

Due to the trend towards increasing loading of system components, cable networks are typically loaded at or close to their maximum current rating. Condition assessment tools are necessary to support decisions for acceptable future load limits or patterns. Within restructured networks the lack of a systematic approach to determining the condition of components, can resulted in increased failure rates at joints and terminations.

The reasoned application of condition assessment tools is vital to the improvement or stabilisation of network reliability.

5.6 Geographic positioning and conditions

The deterioration of HV equipment can be dependant on its geographic location:

- HV equipment in rural areas will in general be less affected by pollution than the same type of equipment in an industrial area.
- Very moist environments will give rise to a higher probability of moisture penetration in HV equipment.
- Equipment in coastal areas will be affected by salt and dust, which may lead to a higher failure rates. For example, insulators in HV power lines are relatively sensitive to environmental conditions.

Another influencing factor is that the maintenance and repair costs may be a lot higher in the city than in a rural environment. For example, repairs of power cables within the city are more costly due to pavement repairs, street traffic interruption, security procedures and/or delayed working time (evening and night). These factors which elevate cost and risk are good reasons to perform focussed condition assessment on HV equipment.

5.7 Installation condition

The installation environment of the HV equipment is of importance for selection of equipment for condition assessment. Equipment can be located indoors as well as outdoors, but also directly buried or in ducts. Substations located indoors within a large substation building will not be directly influenced by external weather conditions. However if a transformer is located indoors, the ambient temperature becomes more important when considering the deterioration of the transformer, as convection cooling is less effective indoors than outdoors.

Cable systems can be installed direct buried or in ducts, both methods have advantages and disadvantages. The main advantage of burying cables directly in soil is a much lower installation cost. The ease of trenching and laying of cables results in less splicing, repairs of the cable can be performed at the location of the damaged part, this is particularly the case in rural sites The surrounding soil maintains the cable mechanically in place and allows a better heat dissipation (depending on the soil thermal conductivity) permitting a higher load. However, with this method it is more costly to reopen a trench for repairs or replacement; also fault locating is more difficult.

With duct systems, most commonly used in cities, cables can be easily and independently installed and replaced, at a much lower cost. Duct installed cables are also protected against being dug up and any weak links can easily be checked and repaired. The main disadvantage of duct systems is the cost, but in the long term it can be the most economical method for multiple cables.

6 Factors that influence and identify the deterioration of critical components

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MATERIAL AND DESIGN
SPECIFICATIONS
OPERATION
ENVIRONMENT
HUMAN HANDLING

HV equipment can comprise static or dynamic subcomponents. In order to identify the HV equipment that may be degraded, it is useful to study the influence factors of deterioration.

It is known, that the deterioration of HV equipment is inevitable. To reduce the deterioration on-site maintenance and diagnostics are performed. With regular maintenance, the equipment is kept in a good condition. The maintenance is performed to arrest known deterioration mechanisms. Measurements and maintenance actions are focussed on possible or known failure mechanisms. Additionally, during these maintenance activities, new signs of deterioration may be identified and the maintenance package will be adjusted accordingly.

Each type of insulation will have its own characteristic type of degradation and aging. Increased efficiencies result if the most appropriate methods for an insulation type are used. Using a power cable example, the condition of the insulation in a power cables is determined by the condition of the insulation at the weakest spots, as well as the overall insulation degradation due to aging. Thus there are two complementary approaches available for assessment:
- diagnostics to investigate the localized defects and
- diagnostics to investigate the global insulation degradation.

In table 2, an overview is shown of typical insulation defects which may occur in power cable insulation [7]. Based on these insulation weak-spots local insulation breakdowns may occur at different voltage stresses. When this occurs, partial discharge (PD) measurement will be sensitive to the discharging weak-spots (insulation defects, degradation products) in the cable insulation.

From early on it was discovered that a combination of measured partial discharge (PD) quantities could be used to recognize discharging defects. In particular it was determined that a good criterion was to reject the object under test if it exhibited PD magnitudes above a certain level when voltage was below its operating voltage (U_0).

As test equipment evolved, the ability to perform phase-resolved PD analysis became available. This lead to the identification of particular patterns of PD for specific defects [Cigre Brochure 229].

For cables in service the maximum allowable voltage stress is $1.7U_0$, with U_0 the line to ground voltage. This stress level is in accordance to [20]. The PD inception voltage PD_i and PD magnitude as a function of the applied voltage up to $1.7U_{0,}$ are essential for interpreting the condition of the cable insulation.

Table 2: Typical insulation degradation processes for distribution power cables

Accessories	interface problems → PD → tracking insulation hardening → cracking → PD conductors issues → overheating → cracking → PD local field concentration → PD
Extruded Insulation	water trees → electrical trees → PD insulation voids → delaminating → electrical trees → PD local field concentration → PD
Paper/Oil Insulation	oil leaks → dry regions → overheating → PD water ingress → load effects → overheating → PD local field concentration → PD

Dielectric losses may have different physical origins. We know that for instance the dielectric losses in insulation can be divided into 4 components:

- conducting losses by free charge carries: ions or electrons
- polarization losses
- ionization losses by PD's
- Interfaces losses

whose sum results in the measured ***tan*** δ of the insulation, this measurement though cannot identify these components individually.

Dielectric aging of XLPE insulated cables changes the morphological properties of the insulation. As a result, due to physical and chemical processes the transportation and storage effects of electrical charges locally increase the electrical field at interfacial boundary layers. Moreover, impurities at the inner semiconducting layer lead to a growth of vented trees which often develop into an electrical tree. Changes in the bulk material resulting from cracking of the amorphous – crystalline regions can lead to micro-voids or an initial breakdown.

Table 3: Characterisation of on-site diagnostic parameters of cables

Condition assessment	Type of diagnosis	Important parameters
Weak-spots	PD diagnosis	- PD_i - PD magnitudes at voltages up to $1.7xU_o$ - PD location - PD patterns
Integral condition	Dielectric losses	tan δ behaviour at voltages up to $1.7xU_o$
	RVM	- Voltage amplitude, shape and time behaviour
	IRC / PDC	- Current time behaviour - Polarisation and depolarisation
	FDS	- tan δ behaviour over wide frequency range.

It follows from table 3 that with regard to diagnoses, several parameters need to be measured as a function of the applied test voltage. Moreover the following has to be taken into account:

- Experiences have shown [10] that the observed changes in the PD inception voltage (PDIV) in combination with PD levels at PDIV and the nominal voltage U_o are a good condition indicator.
- Moreover the increase of PD activity up to $1.7U_o$ is an important indicator, providing information about PD activity at voltages higher than the operational stress, which may routinely occur during the service.

Dielectric response methods – RVM (return voltage measurements), IRC (isothermal relaxation current), PDC (polarisation and depolarisation currents, FDS (frequency domain analysis) are non-destructive test methods, with voltages of typically less than 2 kV, which are able to give quantitative results. These comprise both time and frequency domain methods. In general, mathematical manipulation of results is able to convert the results from one domain to the other. Each method though, within its own natural domain, will have its own diagnostic criteria.

It is useful to have alternative testing methods which can detect degradation parameters under low stressing condition. However in a determination as to the serviceability of an insulation system, one often then has to resort to high voltage site tests. When using HV, the maximum voltage level for on-site diagnosis involving a cable, should not generally exceed 1.7 U_o (max voltage stress anticipated during the service life). However, higher test values may be applicable if indicated in standards, by manufacturers or applicable to the cables operation.

6.1 Material and design

Component level considerations are related to the specific construction and materials. The design of HV equipment is specialised and the applied materials are specific to the requirements of HV equipment. When new materials are developed or their use changed, it is not always clear what the aging and deterioration processes will be in future. HV equipment can undergo stresses that were not accounted for in the design. Negative elements in the design or the applied materials, may therefore be a trigger to start a dedicated program of asset management for the equipment. This is applicable even if there is no direct evidence of degradation as the costs could be much greater after the equipment starts to appear in failure statistics.

Insulation materials in HV equipment can be of a gas, fluid or solid type. Aging of these materials will be different and the operational circumstances will influence the aging processes as well. Condition assessment on dry-type power transformers will be different from oil-insulated transformers, mainly because the insulation requires a different approach. For air-blast circuit breakers not only is the deterioration of the switchgear of importance, but also the deterioration of the compressor should be considered. Condition assessment of this ancillary equipment is of importance in cases such as these and can also influence the remnant life decision of the circuit breaker. Cable insulation can be divided into different categories, which can be layered or solid insulated. The layered insulation types usually rely on oil or mass impregnated paper and have a significantly different aging process than cables constructed with solid insulation.

6.2 Specifications

Specifications of HV equipment are made to frame the equipment functions for its intended purpose. Historical specifications however might not meet the current needs in terms of issues such as work practices, maintenance intervals, material composition, nature of consumables, loading schedules and environmental factors. If this results in additional equipment stress, then condition assessments will be required to monitor the performance of the equipment under its actual service condition.

Specification should be updated in accordance with business, regulatory and technical requirements.

6.3 Operation

The operational environment of HV equipment (loading or switching activities) strongly influences the deterioration processes. Both long term and short effects are of importance and may have different consequences. The effect of load cycles on the aging of a transformer are related to the load itself, the design and the ambient temperature. In Western Europe, the yearly load cycle shows (in most cases) a different pattern to the yearly temperature cycle. However, in the Middle East, the load and temperature cycles are in close agreement, as can be seen in Figure 17. In general this correlation implies that the transformer insulation will be aging faster in the Middle East than an equivalently loaded transformer in Europe.

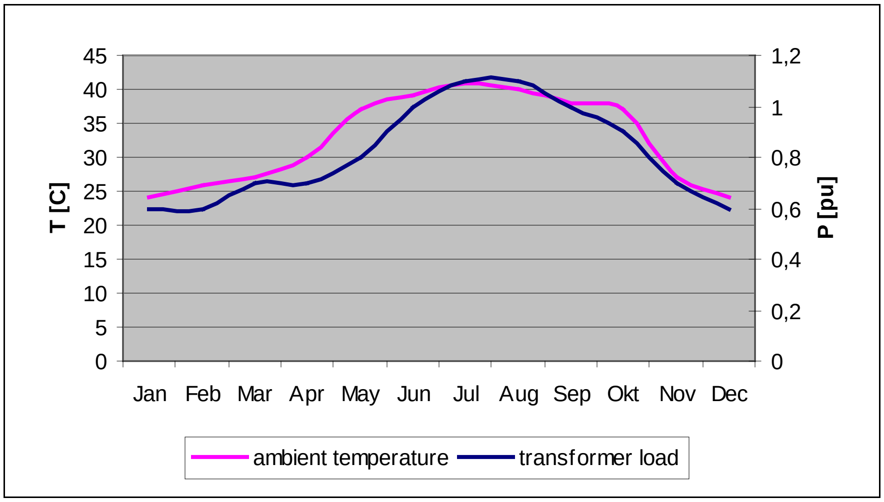


Figure 17: Example of a yearly transformer load cycle and the ambient temperature cycle for a transformer in the Middle East.

Temporarily overloads can influence the deterioration of the insulation. The impact is mainly dependant on the magnitude and duration of the overload and the frequency of its occurrence.

Voltage stresses are related to an enhancement of the local field strength and hence a major cause for initiating insulation defects. This may lead directly to an insulation breakdown, especially during over voltage events. However, in most circumstances, the HV insulation is deteriorated through partial discharges under service voltage, causing a breakdown after a considerable time. Also, temporary over voltages (e.g. as a result of switching) can influence this PD induced deterioration. For example, temporarily over voltages can initiate PD sources, which stay active during normal operation if their extinction voltage is greater than operating voltage.

In cables, water treeing is related to the electric field inside the cable’s insulation in the presence of water. The literature shows that these develop through changes to the physical and chemical factors leading to charge transportation and storage effects, resulting in an increase of the local electrical field. This electrical field leads to electro-dynamic forces at interfacial boundary layers. Impurities at the inner semiconductor layer are often starting points of vented water trees which may convert into an electrical tree. Changes in the bulk properties of the material resulting from cracking of the amorphous – crystalline regions can lead to micro-voids or an initial breakdown. Figure 18 shows a polymeric cable insulation just prior to electrical breakdown occurring.

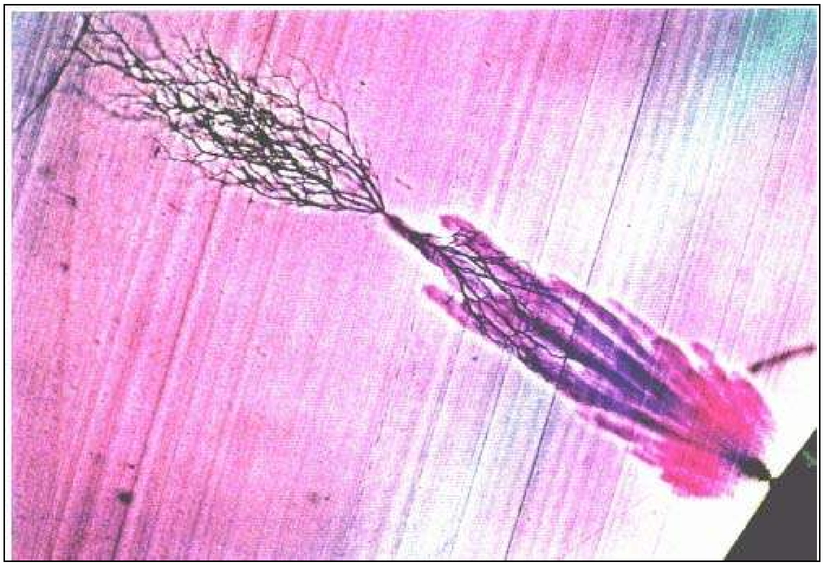


Figure 18: Water and electrical treeing

Switchgear represents a system with both dynamic and static HV and LV elements. The combination of elements results in different deterioration processes. Fundamentally switchgear should operate when it is required to. This means that the driving mechanisms and the contacts should function smoothly when a switching operation is initiated.

Switchgear in an industrial power supply will deteriorate differently than switchgear in the power network of a utility. Industrial switchgear often operates very frequently, which implies wear of the moving parts and therefore faster deterioration than expected. On the other hand, insufficient switching, which can often occur in utility networks, can cause the moving parts to get stuck (for example through hardening of grease).

Off-load tap-changers are also switching elements that are infrequently used, many tap changer failures have resulted from changing taps on off-load tap-changers without exercising the contacts to reduce contact resistance. High resistance contacts can also occur in on-load tap-changers that work within a limited range due to system conditions or requirements.

6.4 Environment

The environment where HV equipment is situated is a significant factor in introducing defects. HV lines in a tropical environment have a higher probability of being affected by algae or plant growth than in other areas, as shown by Figure 19. Also, wear on suspension accessories of HV lines in a windy environment will occur much faster than in other areas.

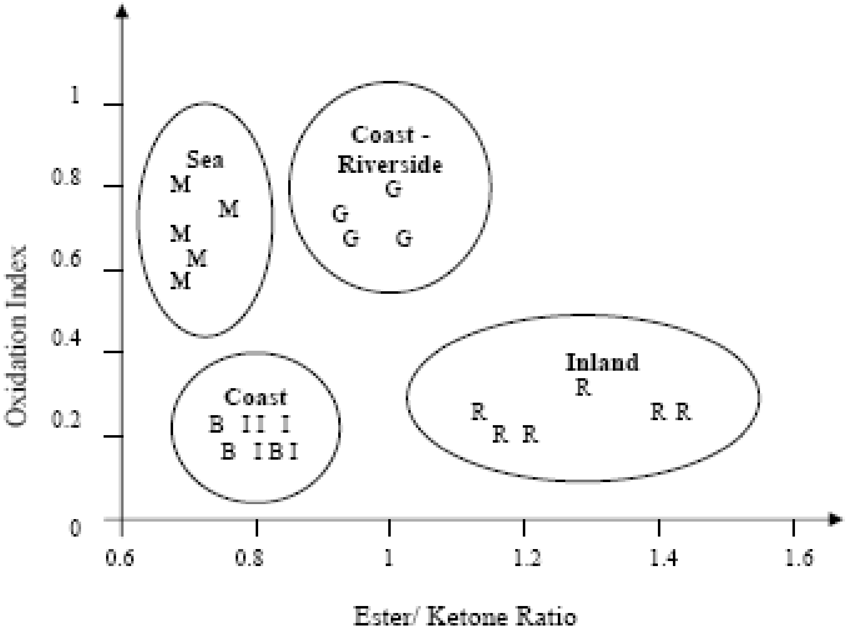


Figure 19 Influence of the environment on the insulation condition of outdoor insulators [15]

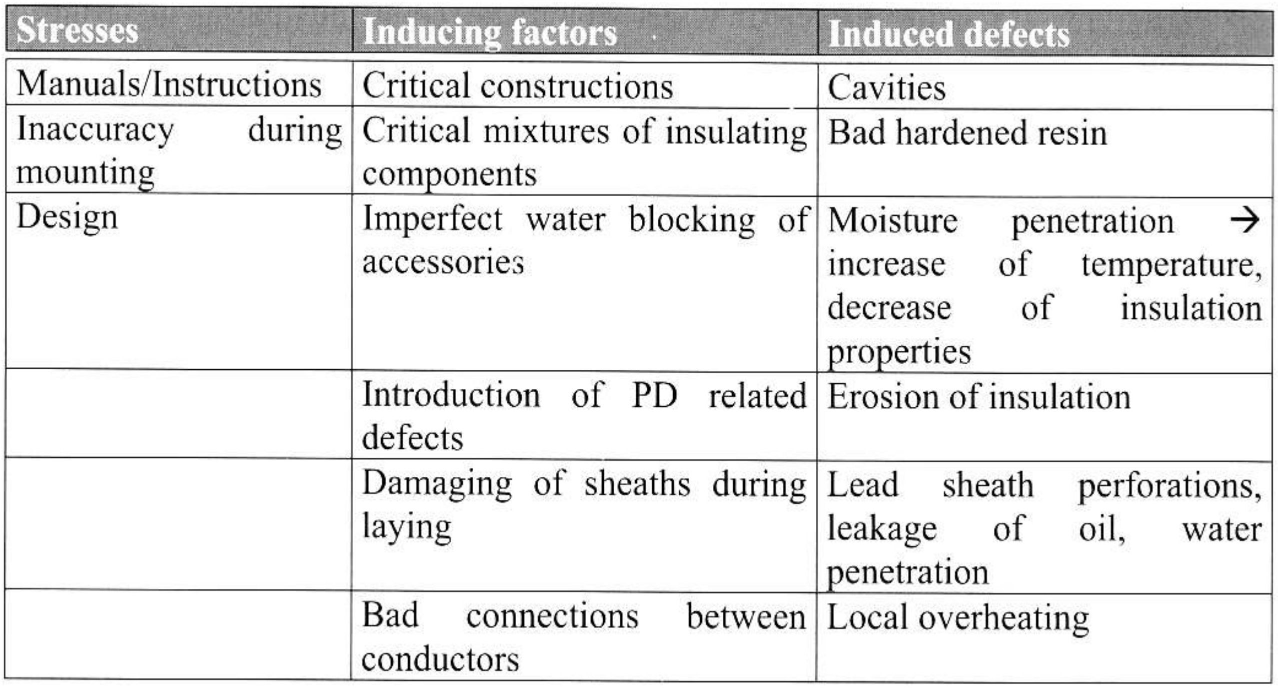
Power cables can be situated under the ground water level, which means that the water blocking system of a cable has to be perfect. Also, poor or changes to soil thermal conductivity may cause the cable to warm up, which will accelerate the deterioration of the insulation. Stray currents from train tracks can result in perforations of the sheath in the same manner as chemical attack, resulting in moisture ingress and deterioration of the insulation.

6.5 Human factors

The on-site installation process of HV equipment is an important element in the condition of the plant. In general these human factors, in the factory as well as in the field, should be detected during the Factory Acceptance Test (FAT) or the Site Acceptance Test (SAT). Unfortunately not all the human errors are able to be detected. For example in cable accessories, incorrect assembly may be an accelerator for the deterioration of the insulation, which may not be detected during the SAT. Installing cable accessories is demanding work, where many external factors (competence of staff, weather, soil, tools, and time pressure) are of influence. So, even if the work is performed accurately, other factors can result in small defects which can accelerate insulation deterioration.

All human factors can bring new deterioration processes in the system (table 4). E.g. maintenance induced failures are one of the main reasons for failures. One of the main reasons for cable outages in the Netherlands is excavation activities around the cable route, which result in damage to the cable systems, either directly through breaching the insulation or through allowing water to penetrate into the cable insulation leading to breakdown. It must be acknowledged that cables are particularly susceptible to changes to their environment. These can result from unforeseen effects such as adjacent digging which reduces the moisture content of the surrounding soil and caused a section of the cable to run at a higher temperature and therefore age faster than the other sections.

Table 4 Summary of categories that cause different types of deterioration within cable insulation as a result of human factors [7].



Stresses	Inducing factors	Induced defects
Manuals/Instructions	Critical constructions	Cavities
Inaccuracy during mounting	Critical mixtures of insulating components	Bad hardened resin
Design	Imperfect water blocking of accessories	Moisture penetration → increase of temperature, decrease of insulation properties
	Introduction of PD related defects	Erosion of insulation
	Damaging of sheaths during laying	Lead sheath perforations, leakage of oil, water penetration
	Bad connections between conductors	Local overheating

7 Guidelines for selection of suitable condition assessment tools

REPRESENTATIVENESS
NON-DESTRUCTIVENESS
CONFORMITY OF MEASURING PARAMETERS
IMMUNITY FOR ON-SITE INTERFERENCES
POSSIBILITY TO GENERATE ADVANCED DIAGNOSTIC INFORMATION
EFFICIENCY FOR THE MEASUREMENT PROCEDURE AND TEST FACILITIES

Condition assessment tools should be able to detect with sensitivity and selectivity the deterioration processes of an insulation system. In order to apply the correct diagnostic tool it should conform to the criteria set out below.

7.1 Test voltages

According to [23-27] several voltage types have been defined for on-site testing. Based on field experience a number of test voltage types are used for testing and diagnosis. It follows from Table 5 that depending on the particular voltage type used that different effectiveness is indicated [32, 33] for identifying defects.

The application of DC voltages has the longest history in testing laminated insulation. This method is applicable for failures related to insulation conductivity and thermal problems. The test systems are simple, lightweight, cost effective equipment with low input power requirements. DC stresses do not reflect AC operational electrical stresses and are sensitive to temperature. Moreover DC voltage stress does not provide insight into important AC parameters such as partial discharge.

VLF testing has become an accepted test method for voltage withstands tests for all types of insulation in distribution networks. In contrast to DC systems, the continuous 0.1 Hz waveform does not result in space charge formation in polymeric insulation. This though is only the case for integral numbers of cycles and interrupted tests can result in space charge. As compared to AC voltage withstand stresses higher voltage levels are required. Also, compared to AC operational stresses in polymeric insulation, different PD behaviour (PD inception, PD magnitudes) have been observed.

In particular, applying AC test voltages has a long history in laboratory testing of all types of insulation. Over 10 years of on-site testing experience for all types of cable systems has confirmed that on-site AC test are useful for identifying all types of failure mechanisms related to cable insulation. This can also readily be combined with other diagnostics such as PD and dielectric loss measurements.

Developments in power electronics have now resulted in a damped AC (DAC) voltage being available for on-site testing and PD measurements [25-27]. In particular the DAC testing is suitable for all types and length of power cables [28-30, 31, 32].

The on-site use of AC voltages is mostly based on the concept of an over-voltage test. As a result the several aspects have to be considered.

a) Routine HV tests are the most fundamental of all electric tests on insulation.
b) Since the test voltage is higher than the rated voltage it is considered as an over-voltage test.
c) It has been introduced many years ago because the over-voltage test was the only available electrical test.
d) A breakdown of the insulation may occur at the insulation's weak-spot and it can be sometimes accompanied by pre-breakdown phenomena (in-homogeneity with locally enhanced electric field).
e) Regarding electrical over-stress a balance is important between detecting serious defects and avoiding insulation damage.

***Table 5:* On-site testing voltages**

VOLATGE	DESCRIPTION
Alternating current voltage (AC)	AC voltage testing uses alternating current at frequencies between 20Hz and 300Hz is an effective method to in stressing site all types of cable systems. As compared to AC voltage stresses during factory testing and service operation it is recommended for withstand testing. HVAC withstand test: the cable section can be accepted if after application of a selected HVAC voltage stress for a recommended duration no breakdown occurs. Diagnosis: at certain voltage levels partial discharges, dielectric losses can be measured as a function of time/voltage and used for diagnostic purposes.
Damped alternating current voltage (DAC)	Damped AC voltage testing uses damped alternating current at frequencies between 20Hz and 500Hz. In combination with partial discharge measurement it is an effective method in testing site all types of cable systems. Due to similarity in partial discharges occurrence at AC voltage stresses during factory testing and service operation it is recommended for on-site testing and PD measurements. DAC withstand test: the cable section can be stressed with a DAC voltage for a time and the cable section can be rejected if a breakdown occurs. Diagnosis: at certain voltage levels partial discharges, dielectric losses can be measured as a function of time/voltage and used for diagnostic purposes.
Very low frequency voltage (VLF)	Very low frequency (VLF) voltage testing uses voltage with frequencies up to 0.1Hz. Due to much lower frequency as compared to power frequency AC voltage stresses, VLF testing relies on breaking down insulation during the testing interval. VLF withstand test: the cable section can be rejected if after application of a selected VLF voltage stress for a recommended duration, breakdown has occurred. Diagnosis: at certain voltage levels partial discharges, dielectric losses can be measured as a function of time/voltage and used for diagnostic purposes.
Direct current voltage (DC)	DC voltage testing has been used for site tests on laminated dielectric cable systems for many years. In general testing with DC voltages is not as applicable to XLPE insulation as it does not result in an appropriate voltage stress in comparison to AC tests. HVDC withstand test: the cable section can be accepted if after application of a selected HVDC voltage stress for a recommended duration no breakdown occurs. Diagnosis: at a specified voltage level the total leakage output current can be measured as a function of time and used for diagnostic purposes.

It should be noted that the table is general and the correct source should still be used in the correct circumstances. Also, this does not preclude novel test methods.

7.2 Non-destructiveness

In general applying an enhanced voltage after-laying testing e.g. up to $2.5U_0$ to a defect-free and not aged insulation does not have significant influence on the service life of the cable and has been estimated to reduce service life by approximately one week.

In the case that defects are present in the cable insulation the effects of AC over-voltage are more complex. It follows from Figure 20 that different aspects are important and have to be taken into consideration. Moreover, several interactions are possible between the defect type/location, breakdown and pre-breakdown possibilities and the test voltages applied.

The type and design parameters of accessories interact intimately with the type of defect and the local electric field enhancement. For example, the presence of internal cavities on the outer conductor in MV cables has a lower impact on breakdown strength than the same cavity close to the inner cable conductor. In both cases for MV cables, the low field strength design does not guaranteed breakdown for voids during the on-site testing with AC over-voltages. But the presence of the same cavities in the insulation of a HV cable will probably result in a breakdown. Moreover, in that case prior breakdown there will be significant PD activity in the cavities.

The interaction between the applied AC over-voltage stress and the breakdown depends also on the type of defect. Whether pre-breakdown phenomena e.g. partial discharges appear, depends also strongly on the type of defect. It is known that breakdown of significant non-homogeneities like sharp edges, cavities, and impurities are mostly accompanied by partial discharges. It is also important to understand that when PD is present that the duration and the level of the voltage application are crucial factors on whether there will be a breakdown.

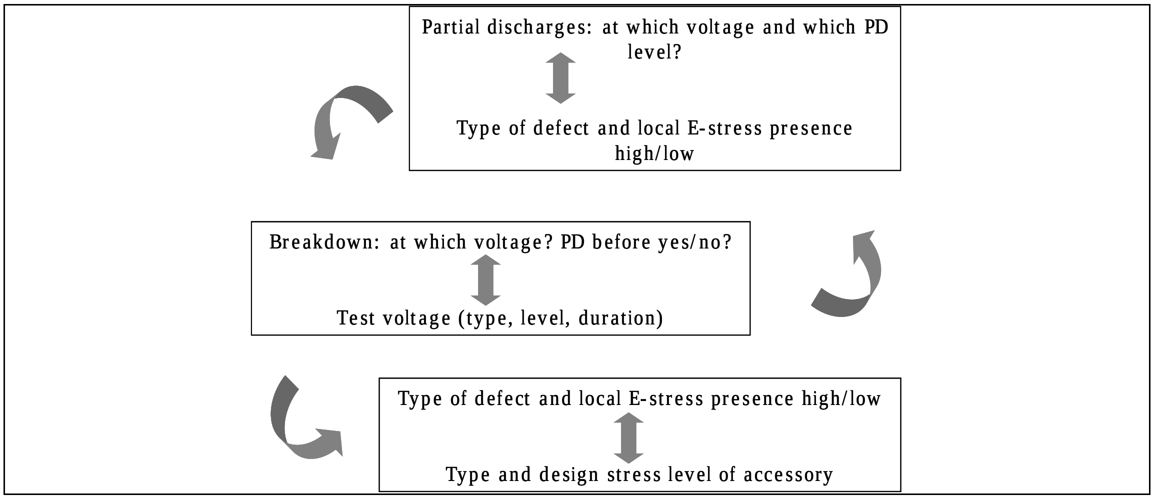


Figure 20: Important issues and the complexity of on-site testing of power cables with AC over-voltages in the presence of insulation defects.

In cables the application of DC voltages for diagnostic purposes often occurs at relatively low levels, such as with RVM and PDC. Transformer tap changer diagnostics are often performed with a current injection into the circuit at levels which are a small fraction of operating current; which are not harmful to the OLTC itself.

As an example, when using the PDC technique the magnitude of DC voltage applied depends on the cable length, the type and the condition of the insulation. For a cable ≥ 4 km, the test voltage is as low as 30V, no matter what the type of insulation. The absorption current of a dry XLPE cable decays in a very short time, so the test can be finished in 200 seconds (100 seconds polarisation and 100 seconds depolarisation) with a test voltage of 200 V. For old oil-paper cable, the voltage level could be 30 V and the minimum test time of 6,000 seconds (3,000 seconds for polarisation and 3,000 seconds for depolarisation).

A suitable diagnostic tool is therefore a tool which is able to detect deterioration within HV equipment in a non-destructive way. The most reliable methods being those that subject the equipment to the normal operating stresses. Even though many of these methods use low voltages the danger to personnel should not be underestimated, as considerable energy can be stored in the reactive elements of plant. As an example, under certain circumstances even a 2A micro-ohm meter can be fatal so care must always be taken.

7.3 Conformity of measuring parameters

In order to be able to compare results from different diagnostic systems, there should be conformity of measurement outputs from different diagnostic systems. In the case of measuring PD, apparent charge of PD pulses in pC and nC. The PD detection methods applied should meet the recommendation of IEC 60270 [Ref 33.03]. This means that the calibration of a system and the detection of the quantities should be performed on a prescribed base, at the terminals of the test object. In this respect, it has to be kept in mind that the condition of the environment and the condition of the test object can have an influence on results. For example, the sensitivity of a PD measuring system depends on the background noise. The ultimate goal in this circumstance is a measurement procedure that excludes the influence of non-related factors.

Insulating oil analysis for transformers consist of oil quality analysis, furfural content analysis and dissolve gas analysis (DGA as per IEC 60599). The standards prescribe what types of gases (concentrations of H_2, CH_4, C_2H_2, C_2H_4 and C_2H_6 plus CO, CO_2, C_3H_6 and C_3H_8) the oil should be analysed for. The analysis of the oil will generally result in conclusions which are independent of the analyst. Recommendations on the follow up actions may be different for each individual.

7.4 On-site interference

Field HV diagnostic measurements should be reliable, with measurements relating to only the parameter of interest. In practical field measurements there is always an element of interference. The effect of interference must be controlled to eliminate as much as possible any ambiguity or error in interpretation of results. PD detection and infrared thermography are examples of diagnostics that can be severely affected. Interference can directly influence the detection equipment or enter the detection equipment through the test object.

For infrared thermography, infrared radiation reflecting from the surface of interest will directly affect the result; typically the sun can greatly disturb the measured temperature. Care should be taken in the measuring technique so as to minimise these errors and if unacceptable then to measure at night.

In the example of rotating plant PD measurements, the measured signals will not only yield PD pulses, but also a large number of disturbance signals. Distinguishing PD pulses from the others is a crucial step in the assessment of stator insulation. In [12] the disturbances regularly measured on-site were classified into seven categories, see table 6.

Table 6: Seven categories of disturbances found on-site.

Nr.	**Name**	**Description**
A	Thyristor pulses	Pulses originating from thyristors in power electronics equipment. For example the exciter of a turbo generator.
B	Radio signals	AM Radio broadcasts can couple into the PD sensor and swamp the PD pulses.
C	Corona	Corona discharges (e.g. on the high voltage line) can be measured and interfere with the interpretation of the measurement.
D	Cross-talk	For on-line PD measurements cross-talk of the PD signals might be present. For example: the PDs from yellow phase are measured on the PD sensor of red phase.
E	PDs from other HV equipment	Other high voltage equipment, for example the step-up transformer, can also produce PD pulses, which are measurable with the PD sensors of the generator.
F	Low signal to noise ratio	The signal to noise ratio can be very low. Especially in an environment where a continuous interference signal couples into the PD sensor.
G	Additional earthing problems	Bad earthing or loops in the earthing circuit which can result in noise.
H	Impedance miss-matching for low voltage measurements	Impedance of the measurement device has to match with the impedance of the other equipment used for the measurement
I	Other	There are various other sources of disturbances, but they are not as common as the ones mentioned above. For example: somebody is using an electric welder, drill, crane or there is a radar installation nearby.

Each type of disturbance has its own characteristic properties. Over the years different types of discrimination techniques have been developed [12]. During the course of this thesis the effectiveness of these recommended discrimination techniques was investigated with a view to their applicability.
Each discrimination technique addresses the challenge of identifying PD pulses in amongst disturbance pulses. A given technique will do better for some disturbance types and worse for others. A list of the discrimination techniques tested is given in table 7.

Table 7: Types of disturbance recognition techniques.

Method		**Description**
A	Phase Resolved Pattern Analysis	The phase resolved pattern obtained from a PD measurement can be used to distinguish different types of disturbances.
B	Directional Sensors	Two PD Sensors are installed: one at the generator and one at the transformer. The arrival time of the pulse at the sensors is used to establish if the pulses originate in the generator.
C	Antenna Rejection	An antenna is placed close to a known interference source. If a pulse is detected at both the PD sensor and on the antenna, then this pulse is rejected
D	Common mode Rejection	Subtraction of the measured PD signals from two channels.
E	VHF Method	The difference in frequency contents of PD pulses and disturbance signals is used to distinguish them from each other.
F	S/N ratio enhancement using smart frequency filter	Boosts the signal/noise ratio of the PD pulses compared to background noise and possibly disturbances
	S/N ratio enhancement using wavelet analysis	Using wavelet analysis it is possible to increase the signal to noise ratio of a PD pulse significantly
G	Typical Time and Frequency Analysis	Uses the shape of the recorded pulses to differentiate disturbance pulses from PD pulses
H	Bridge methods	Uses bridged measurement methods to suppress common mode interference

7.5 Generation of advanced diagnostic information

The objective of using a diagnostic tool is to quantify the condition of an inspected component for asset management decision making purposes. For informed analysis different inputs are relevant, as schematically reflected by Figure 21.

The process starts with answering the following questions.

- What is the type of component?
- How is the component constructed?
- What materials are used within this component?
- What is the function of the component?
- What is the operational/maintenance history? [12]

Next the measured data is an important input. Different measurement data can be collected for one type of component from various instruments. As described in [7], these are often related to the expected deterioration mechanisms. In the case of PD there may be several different representations and quantities to analyse, which can be divided into two main groups:

1. Basic quantities: PD level in [pC or nC], PD Inception Voltage and PD Extinction Voltage in [kV];
2. Derived quantities: e.g. q-V curve, phase-resolved PD pattern, PD magnitude/intensity mappings.

In many cases the phased resolved PD patterns are the most informative. But without expert knowledge (about aging mechanisms and stages, component effects etc) the condition analysis cannot be performed.

The application of component, measurement and expert knowledge are the keys to creating actions that are based on the real condition and will lead to the most effective follow-up actions.

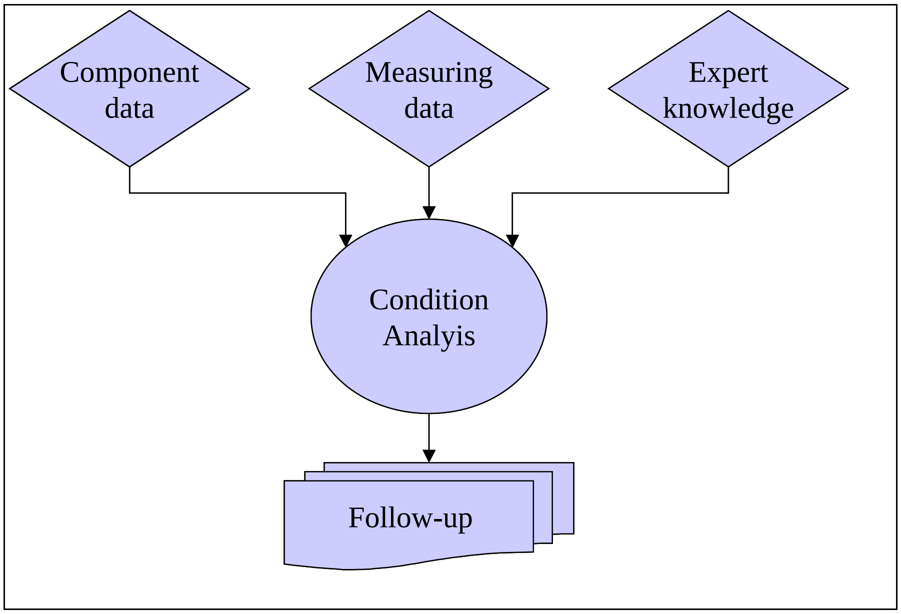
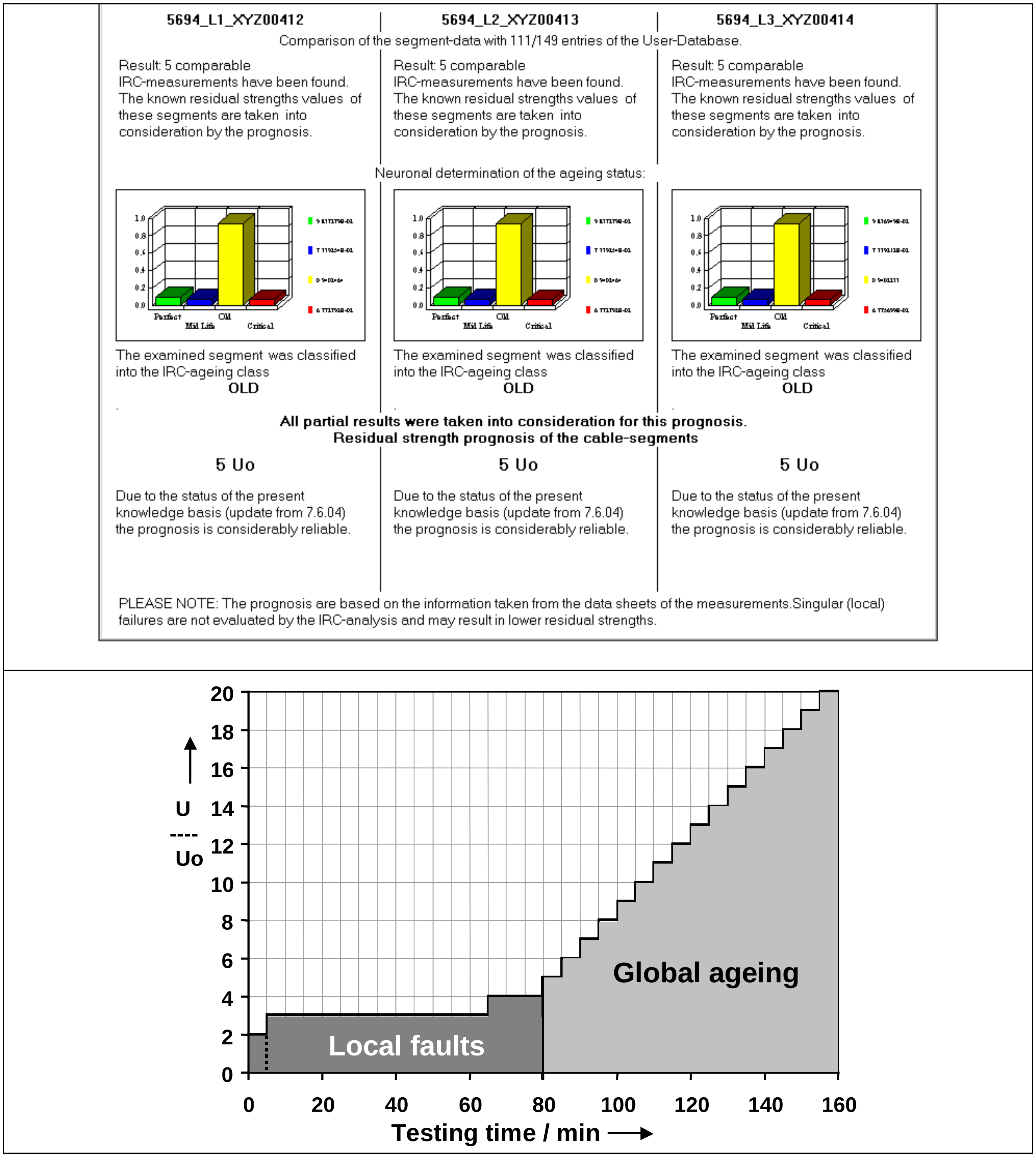


Figure 21: Example of knowledge elements of condition assessment



5694_L1_XYZ00412	5694_L2_XYZ00413	5694_L3_XYZ00414

Comparison of the segment-data with 111/149 entries of the User-Database.

Result: 5 comparable IRC-measurements have been found. The known residual strengths values of these segments are taken into consideration by the prognosis.	Result: 5 comparable IRC-measurements have been found. The known residual strengths values of these segments are taken into consideration by the prognosis.	Result: 5 comparable IRC-measurements have been found. The known residual strengths values of these segments are taken into consideration by the prognosis.

Neuronal determination of the ageing status:

The examined segment was classified into the IRC-ageing class **OLD**	The examined segment was classified into the IRC-ageing class **OLD**	The examined segment was classified into the IRC-ageing class **OLD**

All partial results were taken into consideration for this prognosis.
Residual strength prognosis of the cable-segments

5 Uo	5 Uo	5 Uo
Due to the status of the present knowledge basis (update from 7.6.04) the prognosis is considerably reliable.	Due to the status of the present knowledge basis (update from 7.6.04) the prognosis is considerably reliable.	Due to the status of the present knowledge basis (update from 7.6.04) the prognosis is considerably reliable.

PLEASE NOTE: The prognosis are based on the information taken from the data sheets of the measurements.Singular (local) failures are not evaluated by the IRC-analysis and may result in lower residual strengths.

Figure 22: Example of aging and residual breakdown prognosis of the IRC-method [3, 4] and FGH-step test procedure

In order to aid asset managers in making better decisions, there are many tools available to assist with result interpretation and to compare results with populations of plant. As an example, consider a case of one such tool applied to IRC measurements on cable sections. Figure 22 shows the use of a database with a neural net to assist with overall evaluation of results. Within this database, expert knowledge as well as component knowledge is stored.

Step tests were carried out on the specimen. Figure 22, shows the interpretation of a step test voltage versus time which is useful to distinguish between local faults and global aging.

The measured breakdown test results for the investigated cable segments where 6 U_o for L1, 6 U_o for L2 and 4 U_o for L3. Correlating these results with the breakdown prognosis, the phases L1 and L2 describe a decrease of the electrical strength due to global changes of the insulation. Phase L3 measured with the highest leakage current correlates more with a local weak spot, a long vented tree bridging the insulation or a breakdown based on an electrical tree. Under field conditions this step test method cannot be applied to a cable segment. Using the cable diagnosis system in this example, the condition was determined in the field using a 1 kV voltage with the result in good agreement with the high voltage laboratory measurements.

Within the above described example, diagnostic data, component data and expert knowledge are collected within a database which provides the condition of a particular component. When the condition of the component is known, the right follow-up actions can be determined. These actions also need to be determined in the context of strategic and economic parameters [12].

7.6 Impact of asset operation on condition assessments

Network interruptions for condition assessment testing and maintenance tasks should be as short as possible. In this regard, there is a large difference between the impact of off-line measuring systems and on-line measuring systems, which do not require an asset to be taken out of service.

Following the same method of collecting data is importance for data quality. Figure 23 shows an example of such procedure.

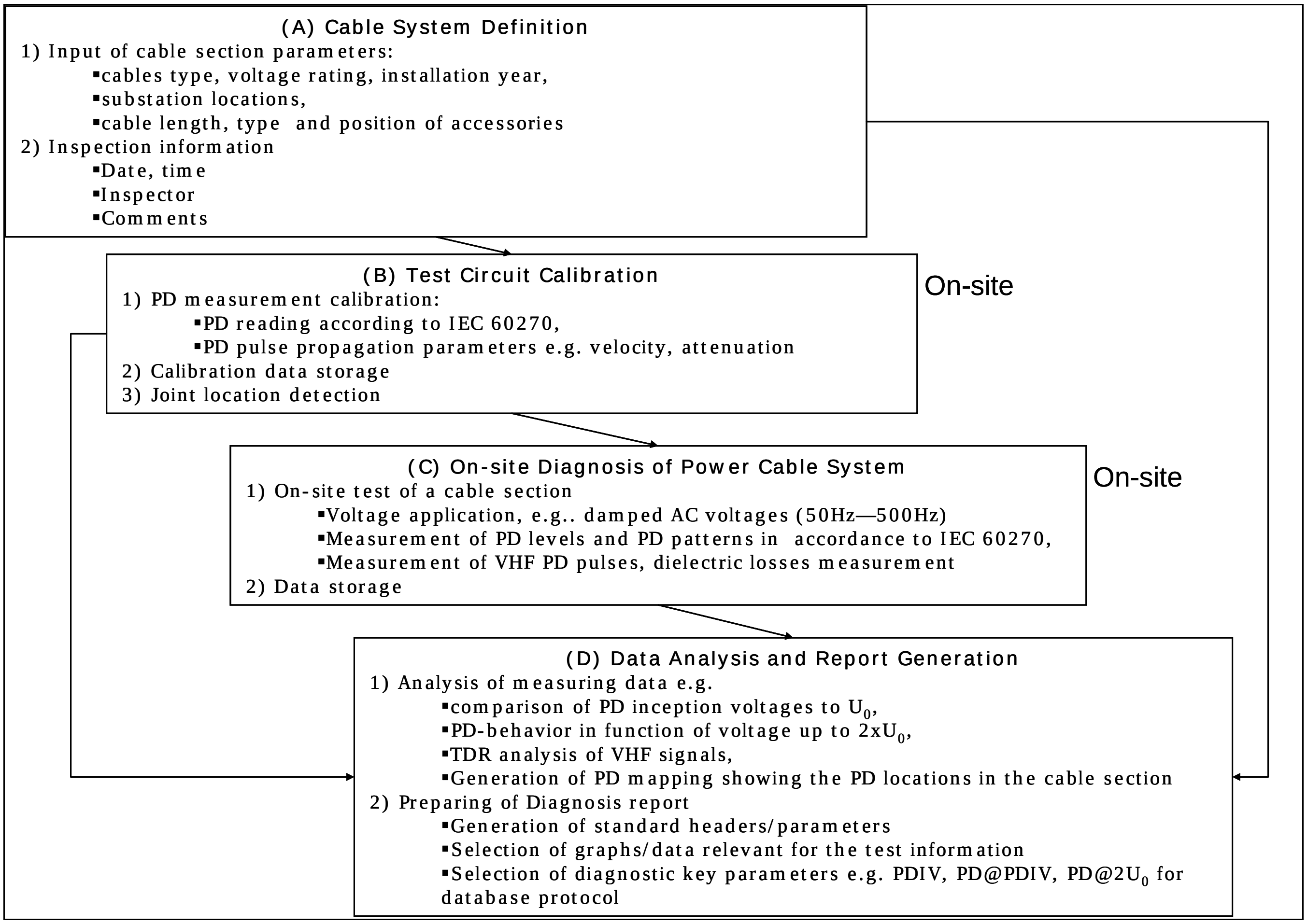


Figure 23: Example of an integrated on-site testing and data gathering scheme for HV power cables [13, 14]. TDR meaning Time Domain Reflectometry and VHF meaning Very High Frequency.

Although the variation in the return-to-service time for different cable condition measurements can be large, in general this is within acceptable parameters for the system operator. As equipment development continues there may be further pressure toward doing more in-service testing, leaving only critical determinations of condition for out-of-service tests.

8 Handling and quality guidelines for measurable quantities

VALIDITY OF THE DATA
STATISTICAL ANALYSIS OF DIAGNOSTIC DATA
CORRELATION OF DATA TO THE DETERIORATION PROCESS (DIRECT/INDIRECT)
DATA MINING

The full potential of condition and maintenance information cannot always be realised by using traditional techniques of data handling and analysis. There are often underlying trends or features of the data that are not evident from the usual analysis techniques. Such detail and trends can be important for the assessment of the best operating strategy for the equipment.

There are also increasing demands from operators and asset managers to fully exploit existing data in order to optimise the utilization of high voltage electrical plant. The methods of extracting full value from such extensive databases, using new analysis techniques, are commonly called Data Mining [8]. In its basic form, data mining is the application of data-driven approaches to find patterns in data sets. The data mining techniques are then used to relate these patterns to the operational condition of the equipment and to provide new knowledge about aging mechanisms, norms and required maintenance activities. The content of this chapter is strongly related to the document of TF D1.17.02, which contains more detailed information related to data handling and data mining.

8.1 Confidence interval of data (Validity of the data)

The confidence interval (or confidence bounds) for collected data is dependent on the amount of data and the relation of that data to the specific processes and mechanisms of degradation. When data analysis is considered in order to asses the health of a component, data history is an important factor. The lack of a substantial data history will make it impossible to discover trends. For example Figure 24 shows a plot of the H2 gas content of a transformer as function of time. Trend plots like these can contain indicators of a defect, degradation processes, as well as information about its severity.

If some of the measurements are missing then the indications may be impossible to interpret or the results may be ambiguous. In this regard it is also important that the database only contain accurate data and that inaccurate result are removed from any analysis as they may interfere with the application of automated analysis systems. Also, the data employed must be comprehensive as changes in trends can be a result of maintenance activities or operational changes rather than changes in insulation condition, e.g. degassing transformer insulating oil.

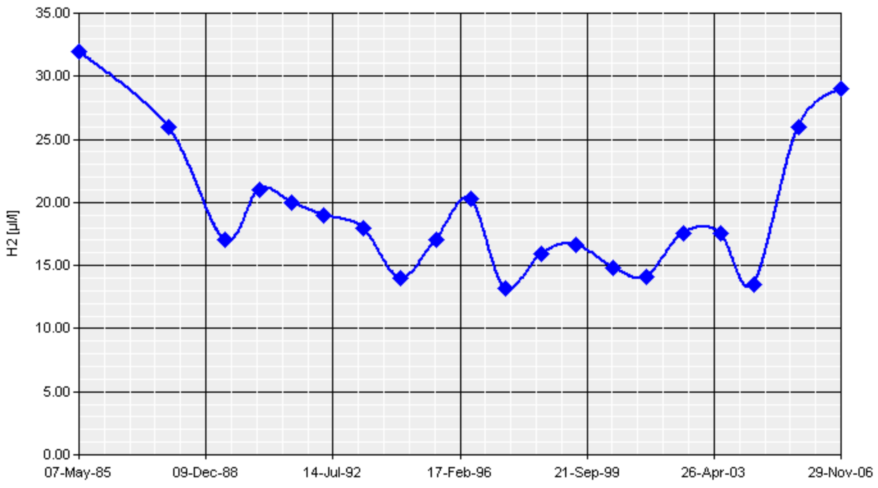


Figure 24: Example of the H2-gas content development in a transformer as function of time

In order to confirm that the component's condition is within the "normal" range of the population, the measured quantity is compared to typical observations. For this to be accurate the parameters need to be compared with the population that has components of the same type. Confidence intervals are then used to reject a sample that does not belong to the population and critical levels are defined through statistical analysis. Incorrect conclusions can result from the following,

- Statistical analysis is performed on measurements not from the same components.
- The number of measurements made on one component is much larger than other components resulting in an over representation of the condition of those components in the population which skews the population.
- Measurements are more often carried out on the components that are thought to have a higher probability of manifesting problems. This will result in a distorted distribution as well.
- Measurement values at or below the noise level are often excluded from the frequency distribution. The reason for this could be that they are not detected or they are thought to be not important. Proper handling of distributions which are (partially) under the noise level is required.

An example is given in Figure 25 which shows how a distorted distribution (caused by omitting measurement values) can influence decision making. In this example PD measurement results are analysed, omitting measurement values below 1200 pC. This results in a different mean and standard deviation. Also, the norm changes from 2056pC to 1999pC. The percentage of the population assigned for further consideration is increased from 2.5% to 3.75%. This means that more components will be selected for assessment than required.

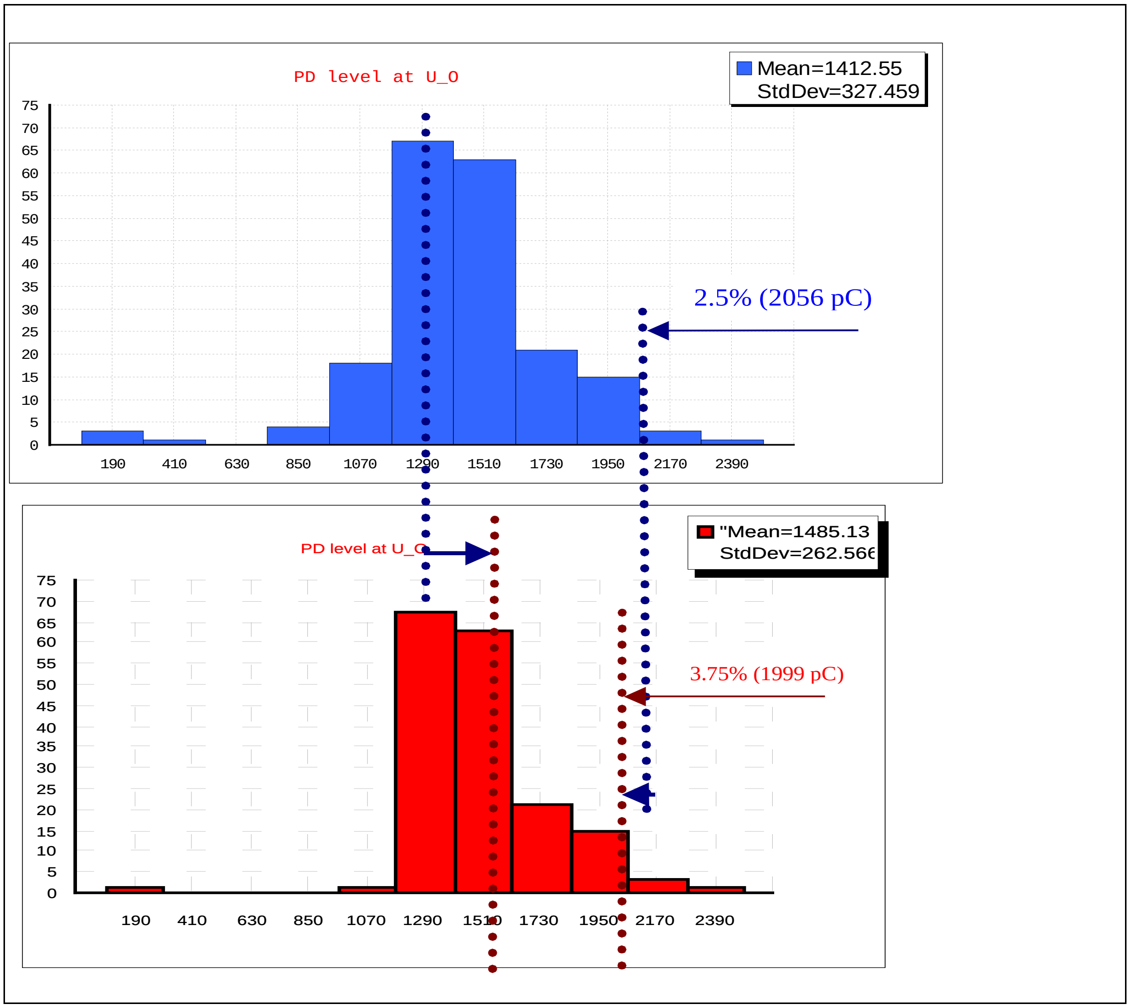


Figure 25: Illustration of the influence of data exclusion in the frequency distribution. The upper distribution function is made with all measurements and the lower one is made by excluding values below 1200 pC. The mean (dotted line in the centre) is shifted to the right and the norm level (dotted line on the right) shifted to the left.

8.2 Statistical Analysis of Diagnostic Data

In order to support data mining, a database is needed in which all the measured data and failure information can be stored and analysed. The general features of such an approach are shown in Figure 26, where data mining results in three outcomes (A, B and C) [8]. Outcome A refers to new knowledge about aging mechanisms of switchgear components. Outcome B refers to recommended maintenance activities on the switchgear components. Due to the large amount of measurement data stored, operating norms and criteria are continuously updated and fed back to electrical staff in the field as determined by result C.

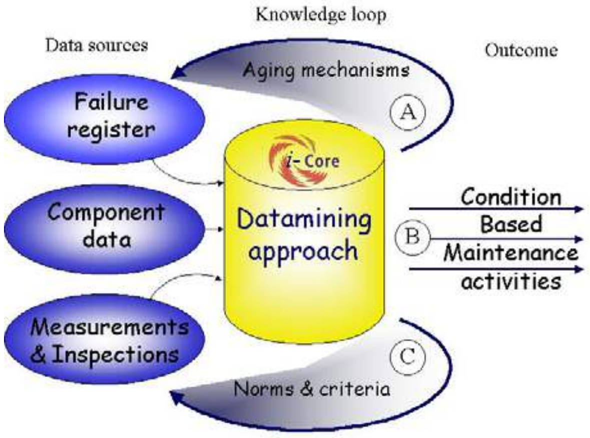


Figure 26: Schematic structure of data mining for condition-based maintenance of circuit breakers [8]

These three outcomes will be explained in detail by practical examples in the remainder of this section.

8.2.1 Aging mechanisms (Outcome A)

For example, in the Netherlands the average age of circuit breakers is about 35 years. Because of the expected wave of investment required, there is a growing need for the determination of aging models of circuit breaker components. A large amount of data, stored in the database system is being used for an investigation of the aging process of an insulation material called material M (fictive name). This material is applied in a large number in this 35 year-old switchgear and has been identified as a critical component because of the cost of replacement and the consequences for the environmental in case of a failure (insulating oil).

For measuring the condition of the material M, a loss current (tan δ) measurement was being used and if tan δ was above 10% the material M was dried in an oven. If tan δ is above 23% the circuit breaker was decommissioned as the material was determined to be irreparably damaged. The ultimate goal of this data mining exercise was to find, from the population, the most reliable parameters that were indicative of the failure mechanism of material M. Because material M is enclosed in insulation oil, a correlation was expected between the moisture level of the oil and the tan δ of the material. As shown in Figure 27, there is an increased influence of oil on the aging mechanism when the moisture level is above 11 ppm and a destructive influence above 24 ppm.
However this figure also shows a large

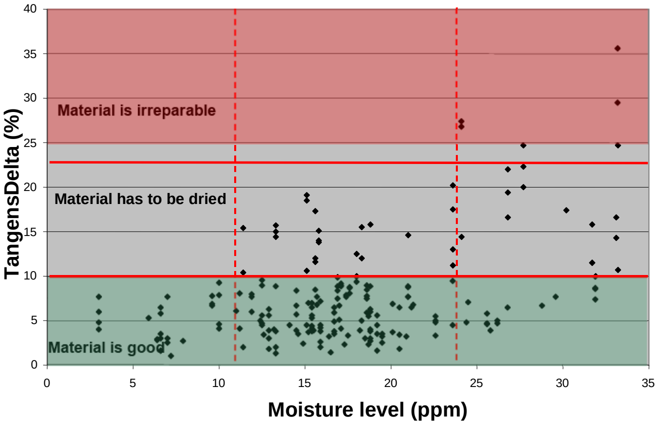


Figure 27: Correlation between moisture level in the oil and tan δ of material M

deviation in the section between 24 and 30 ppm. This means that other parameters besides moisture level also influence the aging process of material M. Further research made clear that the substation location also influenced the aging of material M because of the variety of groundwater in different regions in the Netherlands. Figure 28, shows the correlation between the moisture level of the oil and the aging of material M in a region with a high groundwater level.

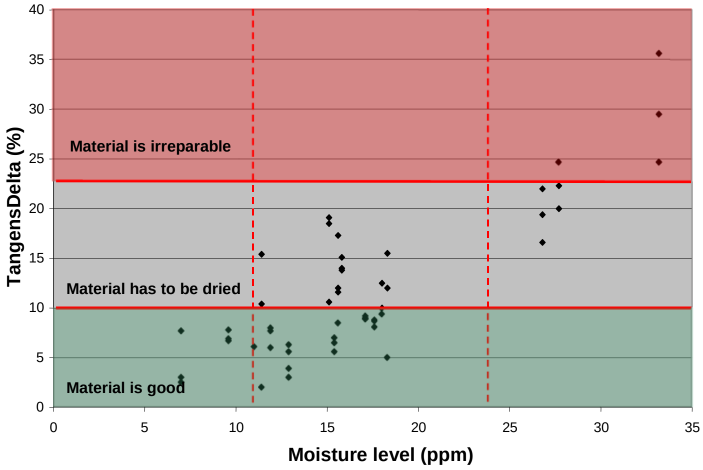


Figure 28: Correlation between moisture level in oil and tan δ of material M in high moisture level areas

Normally only the breakdown voltage of the insulating oil for this type of circuit breaker was measured. However the known influence of the moisture level of the oil on the aging of material M requires a frequent moisture measurement. If a correlation could be found between the moisture level and breakdown voltage of the oil the extra moisture level measurement could be excluded. However as shown in Figure 29, there is no strict correlation between the breakdown voltage and moisture level of the oil in this case. The lack of a correlation between breakdown voltage and moisture level is probably caused by the relatively low moisture level (< 30ppm) and the temperature of the oil (15-20°C). A significant decrease in breakdown voltage will occur above a temperature of 20 °C and a moisture level above 30ppm. Because of the importance of a low moisture level for this specific type of switchgear, the lack of correlation means that both breakdown voltage and the moisture level should be measured.

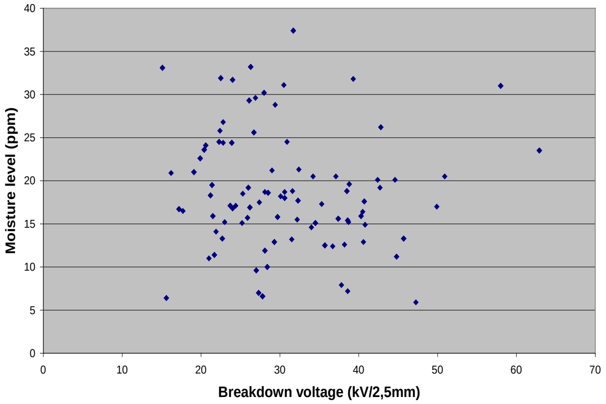


Figure 29: Correlation between moisture level and breakdown voltage.

Detailed data analysis has increased the knowledge of the aging process of critical components of these circuit breakers. Extra attention paid to the moisture level of the oil for these circuit breakers in areas with high groundwater levels, should extend the life of these critical components. The re-conditioning of the oil above a moisture level of 11 ppm in these areas can be looked upon as a precautionary measure for slowing the aging process and the deferring of capital expenditure.

8.2.2 Maintenance activities (Outcome B)

To find a balance between cost reduction, environmental and personnel safety, condition-based maintenance is used world-wide to give support to asset management.

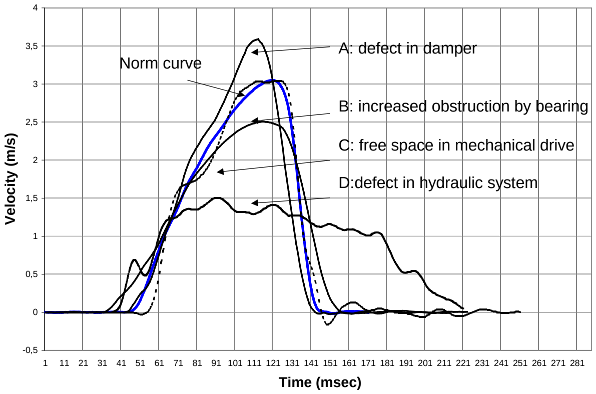


Figure 30: Deviations of the contact velocity curves

Preventive maintenance activities are influenced by the results of condition measurements. For circuit breakers, in addition to inspections, contact velocity measurements have been shown to be one of the best tools to implement condition-based maintenance. Velocity and acceleration curves give information about the condition of the driving system by showing any deviation, obstruction or damper problems during switching operations. In practice assessments are performed by comparison of the measured characteristic with stored reference curves. Figure 30, shows four mechanical faults that can be recognized and this analysis is then used to facilitate detailed maintenance actions.

Condition based methods often eliminate the need for a total overhaul of the apparatus as they cover the active components. However, condition based methods are not a replacement for all maintenance activities. The apparatus consists of many elements, only a small portion of which are active. The condition based methods may not be able to determine the state of all the active elements and may not give any account of the condition of the passive elements which could equally lead to the failure of the apparatus. There must be an appropriate balance between condition and time-based assessment methods based on knowledge of the plant.

8.2.3 Norms and criteria (Outcome C)

Due to the growing importance of measurements as an initiator for maintenance activities, the need for reliable norms and criteria increases significantly.

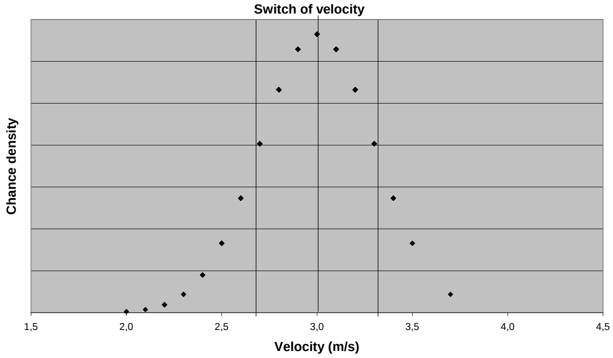


Figure 31: Probability density curve of switch velocity.

Database analysis supports and requires the continuous improvement of norms and criteria. In the case of new measurements and diagnostics, this is often the only way to create reliable norms, due to the relative lack of detailed knowledge from manufacturers with regard to the new and evolving techniques.

Figure 31, shows the determination of a norm for the switching velocity of a specific type of circuit breaker. From different speed curves, key quantities have been derived, including switching time, velocity and acceleration. Each quantity is statistically analyzed to find norms based on the average value and standard deviation as shown in the figure. In this case a norm for the velocity of 3.0 ± 0.3 m/s is derived.

An example of updating norms for contact pressure of circuit breakers is shown in Figure 32. Due to uncertainty about the influence of a high contact pressure on the switching velocity of the circuit breaker, a database analysis was applied to find the correlation between the two quantities.

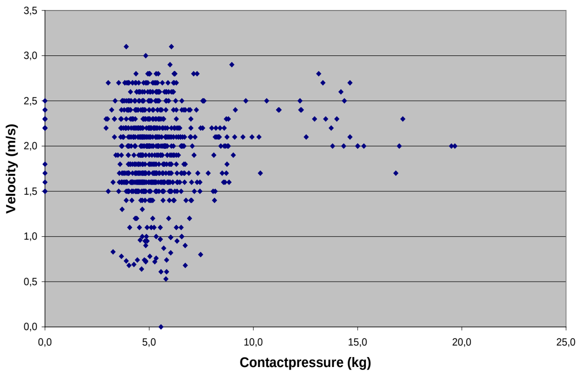
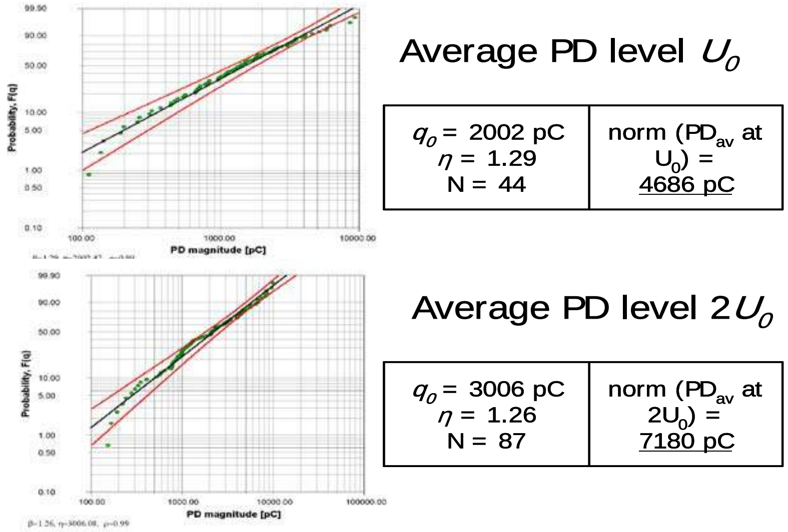


Figure 32: Correlation between contact pressure and velocity.

The influence of contact pressure on the velocity of the contacts is shown in Figure 31. This shows there is no reason to relate the two quantities in setting norms. The power of the drive mechanism has no difficulty in overcoming typical obstructions in the contacts.

Norms based on experience can be obtained from analysing large populations of data. After the determination of the distribution type, the required parameters for the distribution can be calculated. As the distribution represents the population of the utility, the norms that are derived will be more applicable than those derived from other sources [7].



Average PD level U_0

q_0 = 2002 pC η = 1.29 N = 44	norm (PD$_{av}$ at U$_0$) = 4686 pC

Average PD level $2U_0$

q_0 = 3006 pC η = 1.26 N = 87	norm (PD$_{av}$ at 2U$_0$) = 7180 pC

Figure 33: Example of determination of PD magnitude norms for resin-oil insulated cable joints. By using the shape and the scale parameters of the Weibull distribution (with confidence bounds), the experience norm with variance can be calculated.

By using these experience norms the probability that a defect will end up in a breakdown in the short term decreases. For the determination of the experience norms the following assumptions about service-aged components are of importance,

1. only one type of defect occurs or one type of defect is dominant in a specific component type,
2. the criticality of a defect type increases proportionally with the amount of detects surpassing the experience norms,
3. detected PD quantities are independent of the age of the components,
4. PD for some defects may change reversibly before the actual breakdown occurs.

Because of the latter assumption, some defects may eventually result in breakdowns, whereas the PD quantities were analysed below the experience norms. For example, Figure 33 shows the populations of PD amplitude, average and maximum, as obtained at U_o and $2U_o$ for a specific type of cable joint. Using the deviation from the norms as an indicator, the majority of defects will be detected.

A typical path to setting experience norms for PD starts with distributions obtained from field measurements. This ensures that the norms are representative of the plant to be monitored. Norms are initially derived from this data based on 95% of the population. These norms are then adjusted over time as experience and new knowledge dictates.

8.3 Interpretation

During analysis it is important that the data be relevant and in a form that is readily interpretable. Calculations of difference or similarity on three dimensional graphs are more difficult than calculations on a single parameter. Interpretation is often improved if multi-dimensional graphs are broken up into one or more, single parameter graphs. The multi-dimensional graphs are more suited to visual interpretation, but the single parameters graphs are better for calculations.

An example of the above is given in table 8, where the contact displacement curve (as for example is shown in Figure 30) is transitioned into one dimensional values. The contact velocity graph can be translated into different characteristic parameters, which can be easily compared to minimum and maximum values (norms). In cases where these values are not provided by the manufacturer, statistical analysis can be performed more easily on all the collected data for the switchgear type. This enables the definition of new experience norms, as shown in Table 8 for three different types of switchgear.

In determining experience norms, special attention should be paid to the sample size and how well the sample represents the population. The size of the sample will influence the confidence level; with larger samples resulting in higher confidence in results.

Table 8: Derived parameters obtained from a two dimensional graph (measurement). For the different types of switchgear, norm levels can be determined for each parameter. The bolded values are abnormal for the Type 2 switchgear in his example, because they lay not in the range of minimum and maximum value.

	Derived Measured Value	**Type 1**		**Type 2**		**Type 3**	
		Min	Max	Min	Max	Min	Max
T_uit	66	50	70	50	60	30	40
V_c,uit	**1.2**	1.4	1.8	1.6	2.2	2.0	2.5
V_uit,max1	2.1	-	-	1.9	2.5	2.0	2.5
Vuit,max2	1.9	1.6	2.0	1.9	2.5	1.6	2.0
Ts_uit	27	23	35	23	35	3	5
Ts_uit,tot	200	-	-	175	225	225	275
S_uit,eff	150	140	150	146	152	145	150
S_uit,max	150	140	150	146	152	145	152
DS_uit	0	0	0	0	0	0	3
A_uit,max	**170**	50	150	50	150	275	350
A_uit,min	-120	-200	-100	-200	-100	-275	-175
U_uitspoel	120	117	123	117	123	117	123
T_uitspoel	**67**	50	70	55	65	28	42
T_uit,magn	**48**	25	35	25	35	25	35
Xc,in	3.4	3.0	4.0	3.0	4.0	0.7	1.3

8.4 Statistically significant subgroups

Analysis and conclusions about the condition of a population of plant and the future maintenance measures are often best made by subdividing the population into subgroups that have correlated failure modes. This can be thought of as a higher order statistic which identifies common factors such as location, operational conditions (load), manufacturer, spares used, age, nature of internal components or even repair practices.

8.5 Correlation of data to the deterioration process (direct/indirect)

To asses the condition of power components indicative parameters are identified. To asses the condition of a cable system for example, parameters like insulation material, dielectric losses, power factor, moisture, partial discharge activity etc, are determined to be factors to consider in assessment of insulation health. Some of these give direct information on the degradation mechanism while others do not. So the properties of measured parameters can be classified as,

- Directly linked to the degradation mechanism or indicator of it.
  E.g. Tan δ of cable system oil is directly linked to insulation degradation.

- Indirectly linked to the degradation mechanism or indicator of it.
  E.g. PD in an insulation material is an example of a symptom. Its presence is not always directly linked to insulation degradation.

8.6 Data mining review

Data mining in the asset management context is a process that allows the automated statistical analysis of large data sets, exposing underlying relationships between data that can be indicators of issues that would benefit from the application of asset management. As the process is to a great extent automated or at least complex and has many parameters that can be adjusted, there is a need to develop expertise in its application. More information about data mining can be found in [15].

9 Guidelines for unified condition qualification and maintenance actions

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UNIFIED FORMAT OF CONDITION STATUS (HEALTH INDEX)
RELATION TO THE SUCCESSIVE MAINTENANCE ACTIONS (CONDITION BASED MAINTENANCE INDEX)
TRANSFER OF OVERALL CONDITION CODES TO COMPONENT LEVEL

There are large amounts of condition data available from different monitoring techniques which enable insight into the condition of components. However decisions about maintenance or replacement are not only based on the technical (physical) condition. As already mentioned in part I, the overall asset management decision considers at least 6 other types of criteria [16]. To simplify the overall decision making process it is recommended unifying the technical condition and successive maintenance activities in different categories [16]. To simplify the overall decision making process it is recommended that criteria and maintenance actions be categorised with codes.

Categorisation is also required for the exchange of maintenance and condition experience on a large scale. If for example, different utilities perform population analyses of a certain type of power cable and they all use the same rankings for technical condition and successive maintenance, it will be possible to share this information and increase the quality of the analyses from a statistical point of view.

Both the technical condition and the required maintenance can be categorised. The technical condition expresses the position of the component in its lifecycle and the maintenance index is used to categorise the required maintenance actions.

9.1 Unified health index

The health index for cables can be divided in categories as shown below, and in Figure 35:
1 New
2 Service aged (serviceable)
3 Strongly deteriorated (extra attention)
4 Near end of life (unpredictable)

9.2 Condition based maintenance index

Practical concerns of power utilities often relate to a decision about the appropriateness of ***repair*** or ***replace***, and then ***which one*** and ***when***?

Whilst many people still use their experience as the basis of decision making, the use of properly applied statistical methods will improve network outcomes. In order to facilitate this it is important that care is taken in application and gathering of statistical data, with consideration to,

- randomness
- independency
- homogeneity
- amount of data

In order to generate a useful history, data should be gathered during a component's entire life, starting with installation and continuing through to the end of its operating life. This can result in a failure rate representation as shown in Figure 34a, often referred to as a bathtub curve. The shape of the curve is characterized by an initial high and reducing failure probability (I), infant mortality region. Then a period of approximately constant failure probability (II) followed by a section with increasing failure probability (III), useful life region. Finishing with a section of steeply increasing failure probability (IV), wear out region. With reference to Figure 34-b and 34-c, the change from approximately constant failure rate to increasing failure rate can occur in different ways depending on what initiated the change. For example, changes following a change in maintenance, changes in environmental or operating conditions. A mode of failure could quickly accelerate under changes in operating condition which could result in greatly reduced component life.

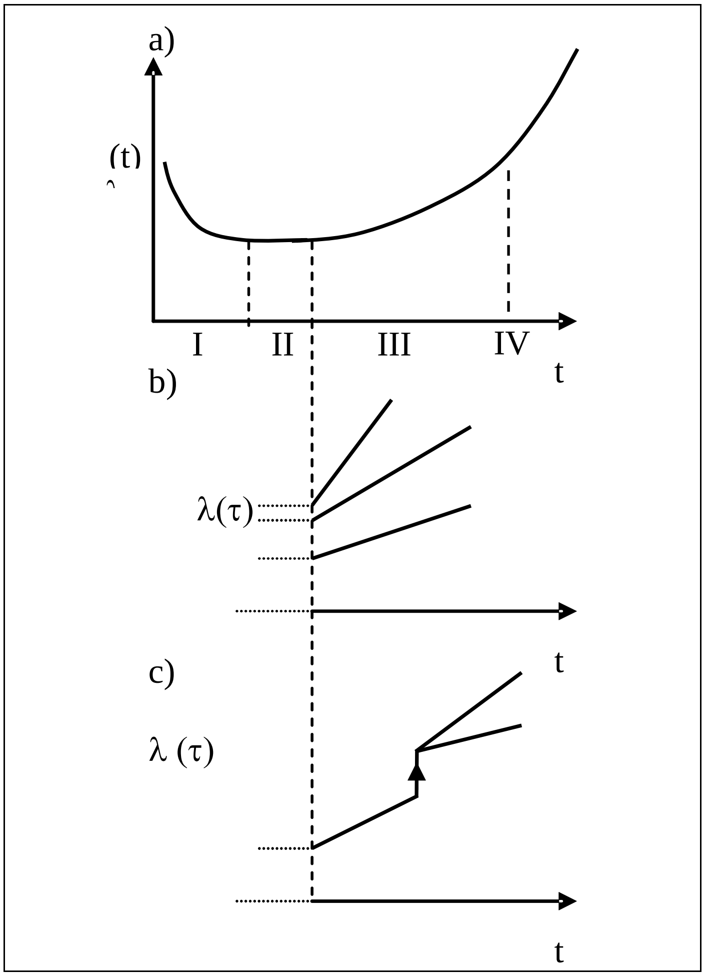

Figure 34: Example of the bathtub curve and categorisation of component age [13].

Both the independence and homogeneity of data will capture physical and chemical factors. The study of influences and constraints connected with given ***events*** ensures a better understanding of the nature of failures, as well as leading to better statistical procedures for analyzing data [13].

Table 9: Example of the relation between technical condition, condition based maintenance index and required actions.

Condition status	**Condition index**	**Service life status**	**Health index**	**Required action**
No defects or aging symptoms observed	9	New or aged	1 or 2	No extra attention required e.g. next inspection in 5..10 years
Certain degree of insulation degradation observed; no harmful defects present	6	Strongly aged	3	Extra attention is needed e.g. inspection within 1 year
Significant degradation observed and serious defects are present. Component is unpredictable	1	Near end of life	4	Maintenance is necessary; e.g. repair or replacement

In order to find a mathematical description of the reliability of network components, the failure probability has to be determined as a first step. The failure probability F(t) is given by equation VI-1. In most cases a two parameter Weibull distribution fits best. The reliability R of a system is defined by equation VI-2 and the failure rate can be calculated by equation VI-3. The failure rate is well known which represents the distribution of age (index) of a network component; see Figure 35. An example is the so called bathtub curve which is a combination of different failure rate curves.

$$\boldsymbol{F}(\boldsymbol{t}) = \int_0^{\boldsymbol{t}} \boldsymbol{f}(\boldsymbol{t})\, \boldsymbol{dt} \tag{9.1}$$

$$\boldsymbol{R}(\boldsymbol{t}) = 1 - \boldsymbol{F}(\boldsymbol{t}) \tag{9.2}$$

$$\lambda(\boldsymbol{t}) = \frac{\boldsymbol{f}(\boldsymbol{t})}{1 - \boldsymbol{F}(\boldsymbol{t})} \tag{9.3}$$

With f(t) the probability function.
The health index for an asset can be divided into 4 categories.

	Service Condition	Description	Weibull Gradient of F(t)
1	new	ok	<1
2	aged	serviceable	=1
3	strongly aged	extra attention	>1
4	near end of life	unpredictable	>>1

The distinction between age index 3 and 4 if often not simple. For this reason indicators from visual inspection or operational data can be taken into account. In Table 9, an overview is given showing the relationship between technical condition, condition based maintenance index and required actions.

Based on the reliability or condition of the component, 3 categories can be defined for qualification of the required condition based maintenance actions,

Condition 9, no maintenance action required as the component is in an acceptable condition.

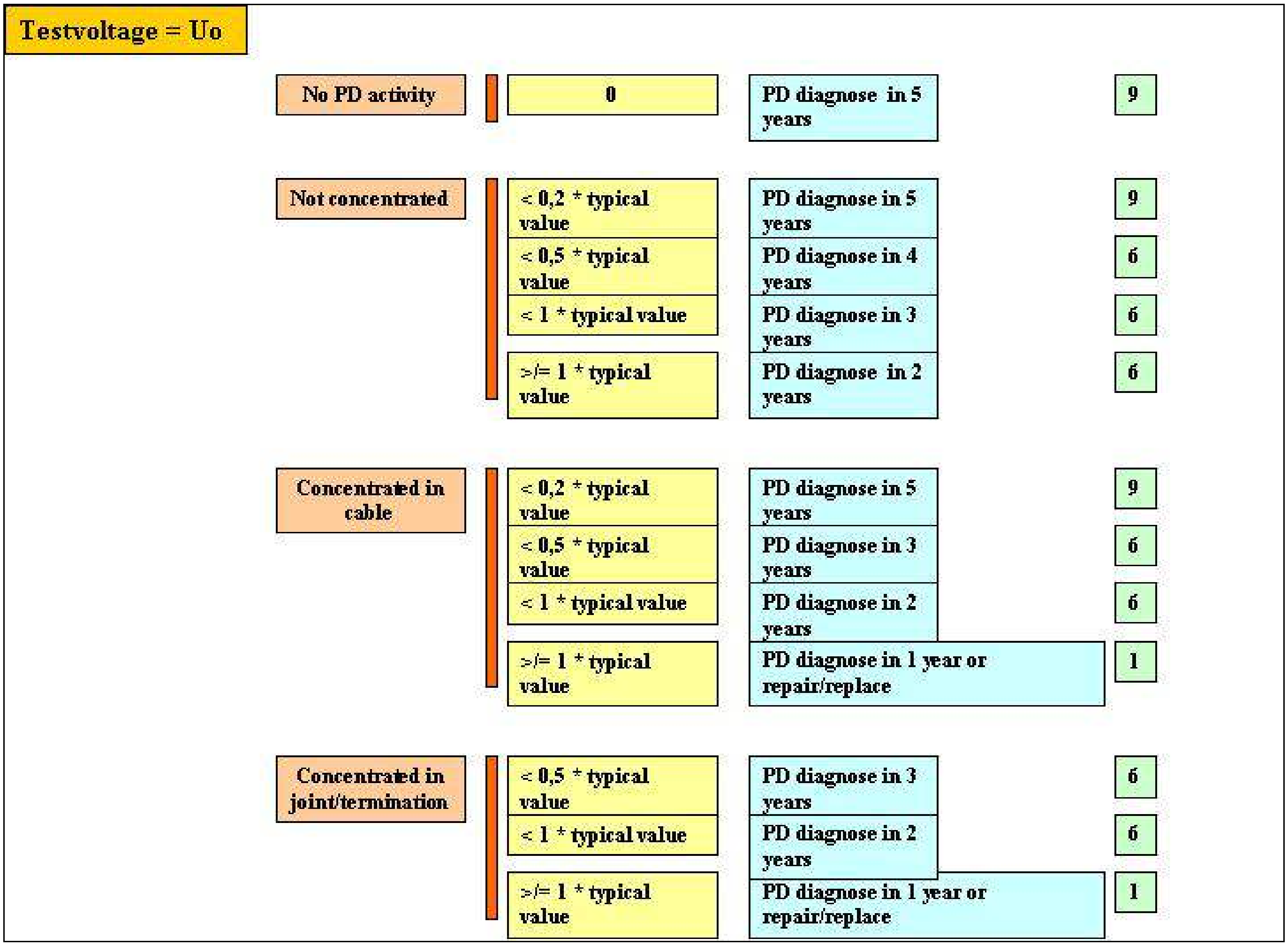

Figure 35: Example of translation of PD results into standardised index for successive maintenance or measurement actions [9].

Condition 6, extra attention is needed (inspections, measurement or maintenance) because the component is aged.
Condition 1, the component must be taken out of service because the component is unpredictable.

The relationship between the technical condition and the condition based maintenance action is described in table 9 and an example for a PD diagnose is given in Figure 36. These limits will be dependant on the requirements and business plans of a particular utility.

9.3 Transferred overall condition code on component level

The qualification of the condition as described in Figure 36 is only for one diagnosis. In practice the standardised condition code of a certain component may be a transferred code from different diagnostics and inspections on different subsystems. For example, transformers can be defined as a component comprising many subsystems with different elements of interest to different groups within the utility, as listed below.

Transformer Elements

- HV Connection
- Bushing
- Winding
- Tap changer
- Insulating Oil
- Oil leaks
- Breather
- Conservator
- Instrumentation
- Protection
- Cooling System
- Pumps
- Valves
- Piping
- Gaskets
- Tank
- Paint/corrosion
- Fire Protection Sys
- Footings
- Bunding walls

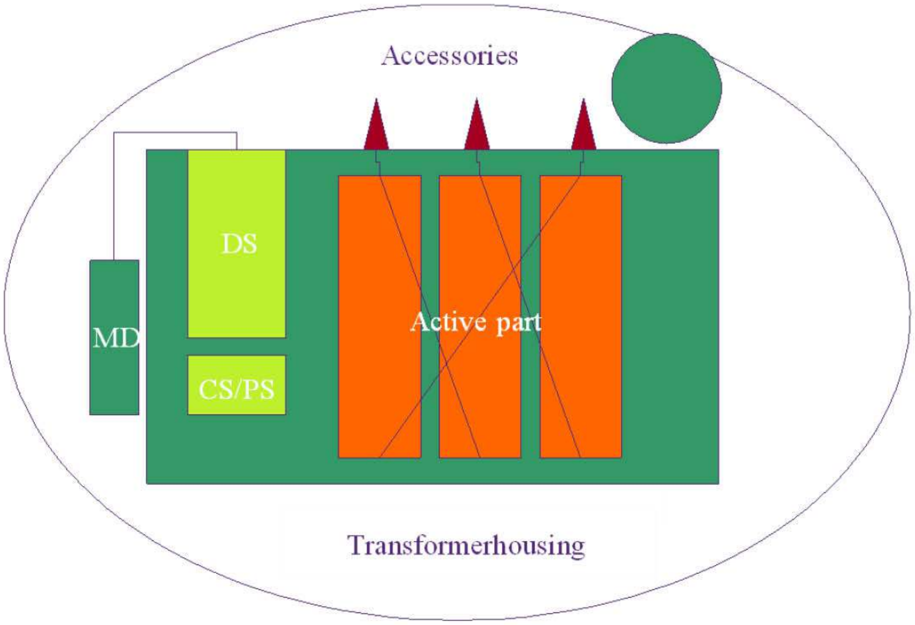

Figure 36: Transformer divided into subcomponents; MD - Motor drive, DS - Diverter switch, CS/PS - Course-selector switch/pre-selector switch, Active part - Core/windings/shielding/etc, Bushings - Primary/secondary/tertiary; Transformer housing - Tank/conservator/radiators, Accessories - Protection relays/fans/auxiliary equipment.

Different maintenance and inspection activities (like visual inspection, OLTC diagnostics, dielectric losses measurements, oil analysis) results in condition codes for each individual subsystem and there are even situations where one specific diagnosis is related to the condition of more than one subsystem. Finally the interpretation of different measurement and inspection results ends up in a qualification of each subsystem. An example of the latter is shown in Table 9.

Each condition code per subsystem can be transferred to one overall condition code for that specific asset. In the upper example, the transformer condition code can be compounded from condition codes of six subsystems: diverter switch, selector switch, motor drive, active part, transformer accessories and protection relays. Each condition code has its own sense of urgency related to the primary function of the transformer. Different solutions for the translation of the individual conditions of the subsystems into an overall condition are possible:

i. Based on worst case scenarios, weakest link principle – this is often the case with power cables, where the chain of different subsystems form the overall condition of a cable;
ii. Based on averaging the condition of the different subsystems – there is a danger that an important subsystem in a bad condition in obscured by other subsystems and results in a catastrophic failure of the asset;
iii. based on the differences of impact – overall condition is determined by using weight factors for each condition code per subsystem.

Incorrect combination of a multitude of condition codes into a single overall condition code may result in erroneous conclusions or undiagnosed problems within subsystems.

Table 10: Example of the application of different tools for a transformer and translation into condition codes.

Subsystem		Maintenance activity/diagnostic	Results	Condition Code		Weight Factor
A	Diverter Switch	Visual inspection	Little mechanical wear Contamination and coal traces	6	6	3
		OLTC measurement	Switching times too large	1		
B	Motor drive	Visual inspection	Mechanical wear	9	6	3
		Functional control	Switching sequence ok	9		
		OLTC measurement	Motor power	6		
C	Bushings	Visual inspection	Small leakage	9	1	5
		Tan Delta measurements	High dielectric losses of one of the LV bushings	1		
		Oil analysis	DGA - OK Physiochemical - suspected	6		
⋮	⋮	⋮	⋮	⋮		⋮

It is of importance to decide which of the condition indictors is most useful for a specific component and which can be combined to provide a useful indication of the condition of an asset. In some cases it may be best to keep the condition codes separate for components. If the maintenance program is specific to subcomponents only then this may also suggest that codes should not be combined.

With reference to the above list, it must be recognised that electrical elements are not the only elements that can lead to equipment aging and failure. Cooling fan faults or valves being incorrectly operated can equally lead to premature failure of equipment. These non-electrical elements will not be considered in the rest of the document but would be considered by an asset manager.

For determining the condition of the tap-changer (course-selector/pre-selector switch) under the prescribed decision process, Figure 37 shows the transfer of measurement results into condition codes.

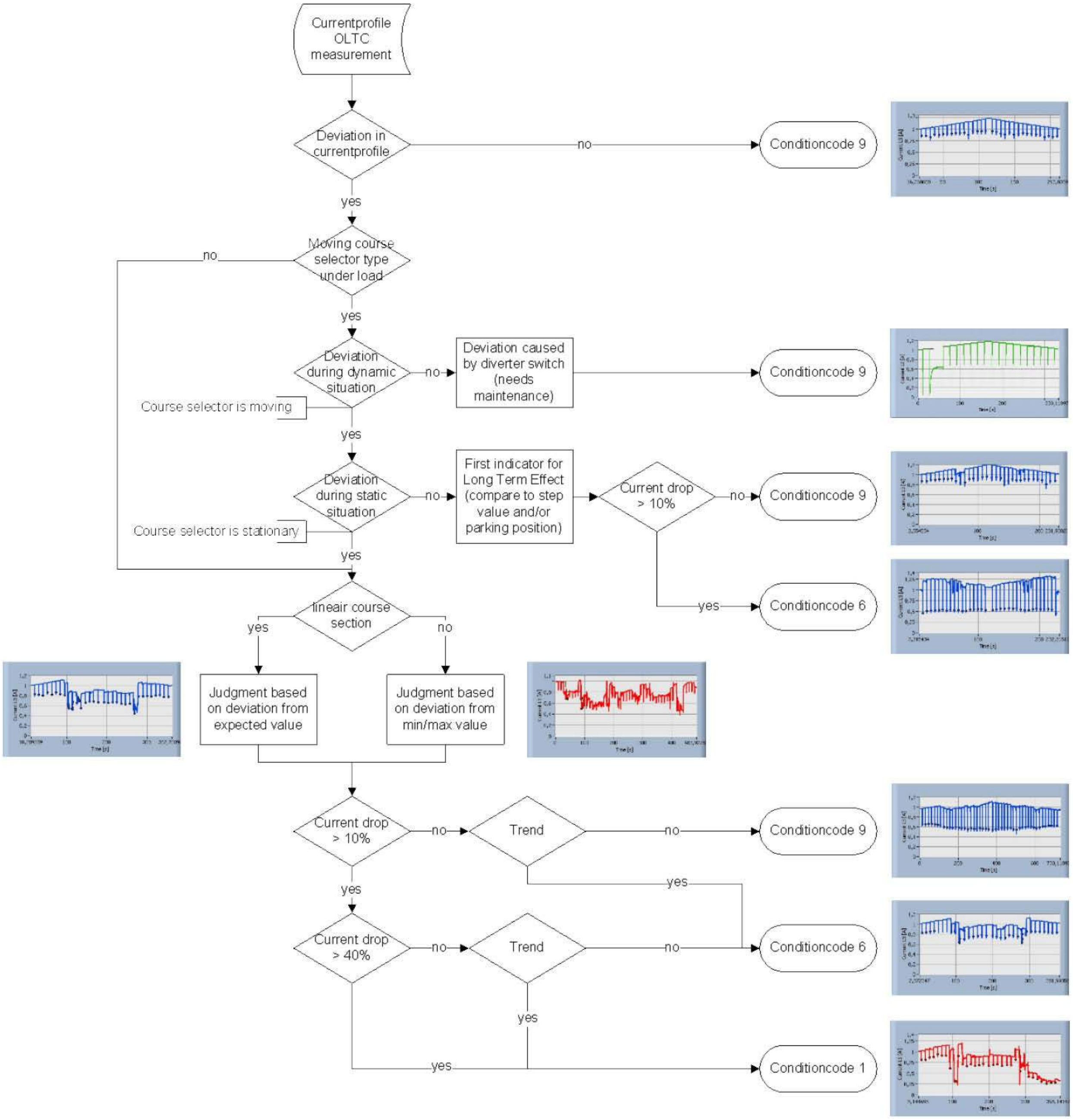

Figure 37: Example of knowledge rule application for Tap Changer Diagnostics as performed using dynamic resistance measurements [27].

Each condition code per subsystem can then be transferred to one overall condition code for the component. For example, a transformer condition code can be compounded from condition codes of six other subsystems: diverter switch, selector switch, motor drive, active part transformer accessories and protection relays. Each condition code has its own importance relative to the primary function of the transformer. Differences in impact can be transferred by using weight factors for each condition code and subsystem. As described in Figure 38.

		Condition codes per subsystem						
Object	Date	Diverter switch		Selector switch	Motor drive	Active part (DGA)	Transformer incl. asseccoires	Protection
		Pollution	Wear					
ALK003 (198908)	06-07-88	1	9	-	9	9	9	9
ALK003 (198908)	12-06-91	6	9	-	9	9	9	9
ALK003 (198908)	19-05-94	6	9	-	9	9	9	9
ALK003 (198908)	04-06-98	9	1	-	6	9	-	1
ALK003 (198908)	13-08-04	1	9	6	9	6	1	9

Figure 38: Example of condition codes at subsystem level.

In summary, the whole process from condition assessment to qualification of components requires a standardised performance terminology, encompassing measured quantities related to the condition of different subsystems. The measured quantities are transferred to condition codes for each subsystem and through the use of weight factors an overall condition code is produced for the whole component.

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