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Final Report

LIFETIME EXTENSION OPTIONS FOR ELECTRICAL EQUIPMENT

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Content

1 Introduction

Power grids comprising various electrical equipment are of major importance to our everyday life. Electrical energy is used for transportation, heating, media or other consumption. But even more important, the industry relies on highly available, reliable access to electricity. Consequently, the requirements for our grid components concerning reliability are high. Nowadays, economic profitability often leads to a strategy change. Instead of early replacement and additional buffer in the grid, optimal equipment use and its lifetime are targeted to limit replacement costs. New digital technologies support this strategy to gather service data and consider them in maintenance and replacement strategies. The energy transition is an accelerator in this process. Due to the high demand for system expansion and reinforcement, keeping existing grid components in service while new ones are installed might be necessary. Particularly for such cases, options for lifetime extension are desired to keep the equipment reliably in service for several years more.

Optimal use of equipment lifetime is not only favoured for technical reasons. The equipment often demands significant natural resources during manufacturing and considerably less for refurbishment or repair. The approach of the circular economy reflects this fundamental fact. Purposeful asset management might help to reach Sustainable Development Goals [1]. Delaying a replacement with reasonable options of refurbishment or repair is economically reasonable and preserves our natural resources.

The approach to optimizing the equipment lifetime is overlaid by several factors, resulting in a complex picture with interdependencies and constraints: The lifetime of grid components is often high, varying significantly due to load or environmental impacts. The energy transition introduces new operation modes and requirements for the equipment, especially in the distribution grids. Finally, the evolution of technologies and the changes in legal and organizational frame conditions further complicate this approach.

This report aims to draw a picture of this complex topic, including major options and aspects of extending the lifetime of grid components. The scope is limited to electrical equipment. Different options for maintenance, service, repair or replacement within the asset management framework are feasible and reasonable, depending on individual priorities. Existing applications are shown, as well as obstacles and limitations. Besides giving the fundamental background, the report includes an overview of diagnostic methods and several case studies to illustrate practical experiences. It should help to get an overview of this topic, even if not all topics are covered in-depth.

2 Asset Management and Lifetime

2.1 Asset Management

Asset management is a coordinated activity of an organization to obtain value from assets [2]. It is an effective tool to help make smarter electric power infrastructure investments. It indicates whether and when to invest in maintenance activities.

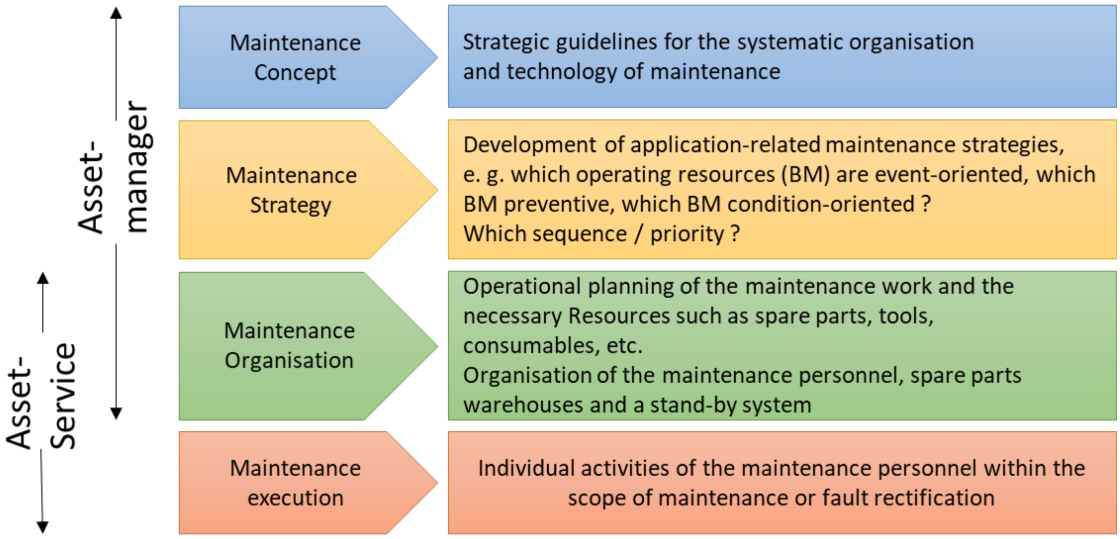
Maintenance not only represents a significant cost block in the profit and loss account but also has a considerable impact on the reliability of the supply of the networks. Until the nineties, the maintenance strategies of the companies were mainly characterized by the striving for high supply reliability. With the liberalization of the electricity markets, the cost pressure on the companies increased considerably because the available financial means for maintenance measures are no longer available to the same extent as before. Strategies have been developed because of the changed framework conditions. These strategies include, among other things, the introduction of reliability-oriented or risk-based maintenance, which involves allocating funds according to the importance of the resources in the system. Another important trend, which is also emerging internationally in liberalized markets, is the use of equipment information systems, which allow better recording of the condition of the equipment, analysis of damage and optimization of the necessary maintenance measures. Parallel to this, the utilization reserves of the equipment are exhausted to the limits under economic aspects. Maintenance and service life cycles are being stretched step by step. These processes will continue in the coming years.

Deregulation and liberalization have intensified the efforts of grid operators to improve the grid and the equipment installed within in technical and economic terms. Asset-management procedures have been introduced to achieve this goal, which was previously only known in the insurance industry. When using these instruments to control the economic efficiency and reliability of the networks, it is essential to consider the technical aspects. Therefore, network operators must deal with technical and management-oriented issues in asset management. These include:

- Maintenance (strategies and planning)
- Condition assessment and evaluation
- Expansion and renewal (strategies and planning)
- Environmental compatibility
- New technologies
- Reliability
- Economic efficiency
- Know-how maintenance and development
- Risk management

Asset management for a network operator must prepare the key decisions which ensure safe network operation, long-term economic success and the best possible return. Since the revenues in the network business are mainly derived from the network charge and are, therefore, more or less fixed, optimizing the profitability of electrical equipment (=asset) is only possible by reducing costs. To this end, strategies must be developed, and decisions on achieving a given supply quality can be achieved at a minimized cost. In addition to expansion and renewal maintenance, condition assessment and service life estimation must be considered to achieve technical and economic optimization. Both the maintenance of the existing network and the future expansion of the network must be considered.

In this context, maintenance and service life issues are of particular interest, as they significantly influence both operating costs and investments and, thus, network costs. Therefore, efficient asset management requires powerful tools and target-oriented strategies for maintenance and renewal. They are a prerequisite for a network operator to be able to fulfil its tasks. By defining strategies and specifications, asset management represents the interests of the asset owner. The basic distribution of tasks between asset management and asset service or service provider around maintenance is shown in Figure 1.



Maintenance Concept	Strategic guidelines for the systematic organisation and technology of maintenance
Maintenance Strategy	Development of application-related maintenance strategies, e. g. which operating resources (BM) are event-oriented, which BM preventive, which BM condition-oriented ? Which sequence / priority ?
Maintenance Organisation	Operational planning of the maintenance work and the necessary Resources such as spare parts, tools, consumables, etc. Organisation of the maintenance personnel, spare parts warehouses and a stand-by system
Maintenance execution	Individual activities of the maintenance personnel within the scope of maintenance or fault rectification

Figure 1: Tasks of Asset Management and Asset Service (or Service Provider)

The following list presents the main criteria to be considered and included in an overall economic efficiency analysis.

a) *Personal safety*

When choosing a maintenance strategy, the extent to which the safety of persons is endangered in the event of a loss of function of a piece of equipment must be considered. Equipment with a potential risk must be maintained properly by the network operator following the relevant regulations due to the obligation to ensure traffic safety or to protect personnel.

b) *A material amount of damage in case of loss of function of a piece of equipment*

The choice of maintenance strategy will include an assessment of the sum of the operational damage and the damage caused by energy not being supplied on time. If substantial damage is to be expected, the maintenance target is set so that the loss of function of a piece of equipment is prevented as far as possible. In doing so, the expenses for maintenance are to be compared to the possible damage. These estimated damages must also include possible environmental and/or image damage.

c) Importance of the equipment for the supply task

When determining the maintenance strategy, the importance of the equipment for the supply task will play an important role. Equipment whose loss of function leads to high failure energy or long supply interruptions is maintained as far as possible so that the probability of an equipment failure is kept low. If the condition of the equipment can be detected via a suitable monitoring or diagnostic system, condition-based maintenance will be applied. If the condition of the equipment cannot be reliably determined, preventive maintenance should be chosen to ensure the required high reliability of supply.

d) Legal requirements

The situation is different for equipment for which certain maintenance measures are prescribed by law. These are environmental protection laws, calibration laws, pressure vessel regulations and other official requirements. As a rule, preventive maintenance is applied here. In the case of certain devices for recording energy quantities, the calibration law permits a sampling procedure to determine the condition and, if necessary, extend the use period.

e) Quantity structure

The choice of maintenance strategy for a piece of equipment may depend on its quantity structure. For equipment installed in large numbers in the network, preventive and condition-based maintenance are usually ruled out for economic reasons. In practice, event-oriented maintenance will therefore be used for this equipment. Therefore, low-maintenance or maintenance-free should be considered for standard material in the low-voltage or medium-voltage network.

f) Maintenance requirements and special stresses

The network operator will generally adapt the maintenance level, especially the maintenance cycles, to the operational requirements and his operational experience. If necessary, the manufacturer's recommendations for maintenance must be considered because, in some cases, manufacturer guarantees are tied to certain maintenance specifications. Preventive or condition-based maintenance is usually used in equipment with significant wear and tear (wooden masts, steel structures, on-load tap-changers, frequency changers).

g) Operating experience, failure, and damage analyses

The operating experience, based on statistics, like failure and availability statistics and failure and damage analyses, form the feedback for optimizing maintenance and a qualified service life estimate. They also form the basis for developing suitable monitoring and diagnostic systems and procedures. They are a prerequisite for selecting a suitable maintenance strategy and a target-oriented further equipment technology development. In this respect, some equipment's error rates and priorities will be considered in the following equipment. [3]

2.2 ISO 55000

ISO 55 000 is the international reference standard for the optimal management of physical assets. It was published in 2014 in response to industry demand for good practice standards in asset management. A central concept of ISO 55 000 is applying a management system to care for the organization's physical assets, referred to as an "Asset Management System" [4]. It is a collection of policies, practices, processes, business rules, procedures, etc., providing governance and direction to the asset management operation.

ISO 55 000 favours a complete and integral approach for assets in an organization where clear communication exists between all parties. It coordinates the life cycle of the assets and strives for deliberate decisions.

The target audience of the standards is:

- Those considering how to improve the realization of value for their organization from their asset base
- Those involved in the establishment, implementation, maintenance, and improvement of an asset management system
- Those involved in the planning, design, implementation, and review of asset management activities

2.3 Lifetime of Electrical Equipment

The lifetime of electrical equipment is a crucial measure within asset management. The lifetime of electrical equipment is usually described as the timespan in which the equipment is in service. The time to take electrical equipment out of service is set after evaluation of wide interests [5].

The **functional end of life** is accomplished when the equipment does not fulfil its relevant functions and has to be replaced from a technical point of view. However, due to outage costs and risk minimization, electrical equipment is commonly replaced earlier, and the risk of failure is still reasonably low when being replaced.

The **reliable end of life** considers the reliability of the equipment itself, security and safety aspects, and interactions with the environment. It is reached earlier than the functional end of life, as soon as the risk becomes unacceptable.

Economic considerations define the **economic end of life**. It occurs when the electrical equipment must be replaced, as it is no longer economical to continue in its current position. Operating, maintenance, repair or replacement costs are balanced with outages and other follow-up costs, corresponding to the importance of the electrical equipment, risk of failures, and others.

2.4 Reasons for Repair and Exchange

a) Load and Ageing

During normal service, the electrical equipment's condition changes due to external and internal influence factors. External influence factors are ambient temperature, UV radiation, rain, pollution, vibrations, overvoltage and transients. Internal influence factors depend on the mode of operation, like (hot spot) temperature, electrical field stress, partial discharges, vibrations or continuous mechanical stress. Table 1 gives an overview of common ageing mechanisms and their relevance. As the temperature promotes most ageing mechanisms and is directly load dependent, the mode of operation significantly influences the electrical equipment's condition.

Table 1: Overview of typical ageing mechanisms in electrical equipment

Origin	**Process**	**Relevance / Dependencies**
Thermal degradation	Pyrolysis, degradation or depolymerization, if provided thermal energy exceeds chem. bond energy (material dependent)	highly temperature dependent
Mechanical degradation	oxidation, leaking seals, cracks in solid material and welding caused by shearing forces, e.g. due to vibration	depending on mechanical stress, important to switch devices
Electrical field ageing	charge carriers are accelerated due to the electric field; collision transfers enough energy to break bonds	depending on field strength and charge carries in a high field area
Partial discharges	field strength exceeds intrinsic field strength for inhomogeneous spots	critical for curvatures, enclosures, holes or cracks in dielectrics; might cause chemical degradation and further issues
Surface discharges	arcing on the surface lead to material degradation	relevant for dielectrics with high surface pollution
Chemical degradation	mainly UV radiation and acids from the environment	relevant for outdoor equipment
Ageing of nondetachable contacts	contact resistance increases due to reduced contact forces or material degradation	depending on contact force, mechanical stress and material combination, temperature-dependent

b) External and Environmental Influences

Besides continuous ageing, the equipment might change its condition abruptly. Besides internal failures, this can also be caused by outside impacts. For example, electrical failures in neighbouring facilities might cause high short-circuit currents, which lead to high mechanical forces, harming the integrity of the equipment. Lightning or switching impulses can cause severe overvoltages and transients. Also, mechanical impacts are possible, like a tree falling into an overhead line or digging into a cable.

All these external and environmental influences are not predictable or plannable and will randomly occur.

c) Outdated Parts

Limited availability of a replacement and spare parts for original equipment is the norm with ageing, when the original manufacturer moves products to an obsolete life cycle phase, typically 10 years after manufacturing ends. Even if still supported by regular manufacturer maintenance, this is a major operation concern on mission-critical equipment.

This concern may worsen when the original manufacturer stops production or the brand is acquired, and the original design is discontinued and often not supported. Regular inquiries to the manufacturer for maintenance, spare availability, delivery terms, and installed base life cycle phase shall be part of the equipment life strategy.

d) Legal or Politic Reasons

The legal framework or politics can drive the exchange of equipment as well. Bans or limitations of emitted by-products, noise, used raw materials, and others can be a reason. A well-known example of this is the electrical switchgear replacement driven in the next future by the willingness to move to SF_6-free products. SF_6 has been used for over 40 years as an insulating and/or arc-quenching gas. But it's very high Global Warming Potential (GWP) of 25,200 [6], is becoming a concern for users, manufacturers and even countries who has to consider the emission of SF_6 in their carbon footprint reporting and policies. For a few years, alternative solutions to SF_6 have been coming on the market, and manufacturers are committed to replacing most of their portfolio of SF_6 products with SF_6 free [6] [7].

On the regulatory side, SF_6 is typically included in so-called “F-gas” regulations, and very few regulations in the world are strictly focused on SF_6 itself [8] [9]. None of these regulations asks to replace Equipment filled with SF_6 before the planned end of life. In CARB and probably in the future EU F-gas regulation [10], the use of SF_6 in new equipment will be banned.

Unfortunately, replacing only SF6 with another alternative gas is impossible, and all the equipment shall be replaced.

Users (Utilities and industries) are also committing to lowering their carbon footprint, and pushed by some recent studies [11] are beginning the anticipated replacement of their electrical equipment before the end of life.

e) Safety Aspects

Safety aspects linked to obsolete equipment and, in particular, to switching technologies need consideration and can be a driving element when deciding on modernization, such as:

- **Fire and explosion hazard:** bulk oil and minimum oil circuit breaker use mineral oil as insulation and interruption; in the event of failure, this can greatly increase the consequences of a fire.
- **PCB oil contamination:** the oil insulation in both transformers and circuit breakers may contain PCB-based oil or be contaminated by such due to oil replacement in the equipment file-span. PCB-contaminated oil, a bio-hazard material, must be treated as special industrial waste and properly disposed of.
- **Asbestos contamination:** air magnetic circuit breakers use such insulating material in the interrupting chambers; while typically stable in operation, it can be released during the circuit breaker arcing-chambers maintenance. Asbestos-based insulating barriers were also used in switchboards. Such material poses a health risk for operators and requires a specific risk assessment and procedures. [12]
- **missing interlocks and segregation barriers to high potential parts**: opening the switchgear doors and removing the original switching device in obsolete switchgear poses electrocution risks.
- **Operation hazard:** operating earthing switches, interlocks and racking a circuit breaker into a connected position exposes an operator to risk when performing breaker compartment physical inspection, breaker swapping or scheduled maintenance.
- **Racking in-out operation** requires moving the original breaker, typically in the several hundred-kilogram ranges, contemporary operating the mechanical links coordinating shutter opening and closing on an energized-busbar switchgear. Original panel breaker interfaces, such as shutter-operation mechanisms or matching primary disconnects, are

vulnerable to mechanical failures that may create safety problems. Furthermore, several obsolete designs demand the operator to access the breaker compartment with an open door.

- **Non-internal arc (IA) resistant switchgear construction:** switchgear cannot contain the energy related to an internal fault originating an arc for a defined protection intervention time. Risk mitigation strategies in the modernization process can reduce the IA energy released with active fault detection protections or provide a safe operating distance to personnel through remote racking and remote operation.
- **Missing arc gas ducts:** the absence of proper exhaust gas ducts, even with IA-classified switchgear, will cause the release of smoke, limiting visibility, and toxic combustion by-products to the switchgear room, making reaching the escape route difficult.

Specific safety regulations and standards [13] [14] address electrical safety requirements and require the evaluation of the arc flash boundary, incidence energy and personnel to wear appropriate PPE accordingly to address IA risk. Such protection requirements, especially in the hot season, may be significantly uncomfortable and increase the operational procedures' effort, inducing different risks due to hurry, lower caution and dehydration.

Updating safety features is therefore increasingly seen as essential by equipment owners, maintenance and operation responsible, who are serious about safety even if such an update is not a regulatory requirement in the conversion process, such as IEEE C37.59-2007 [15].

f) Energy transition and electrical network enhancement

International Renewable Energy Agency IRENA expects by 2050 that electricity will be the main energy carrier with over 50% (direct) share of total final energy use – up from 21% today [16], and 30% in 2030 to meet the 1,5°C target of average temperature increases by 2100 year [17]. That implies an electrification effort in the next 10 years, representing half of the last 100 years of world electrification!

Moreover, the network connecting points, where transformers, switchgear and cables are the bricks, will need to adapt to intermittent energy sources to maintain network stability. It means that current connecting points can become obsolete, and the existing equipment of these critical connecting points can be replaced. These pieces of equipment can still be used in other less critical connecting points and then refurbished.

On the other hand, the lifetime extension of existing equipment is a solution to face the outstanding demands of new equipment that will put their supply chain and cost under pressure.

3 Maintenance Strategies for Lifetime Extension

A maintenance strategy is the management method used to achieve the maintenance objectives. It is the responsibility of any maintenance management to define its maintenance strategy. The type of maintenance contributes significantly to the lifetime of electrical equipment. The European standard EN 13306 provides the following main objectives, which should be pursued when developing a maintenance strategy [18]:

- to ensure the availability of the item to function as required at optimum costs;
- to consider the safety, the persons, the environment and any other mandatory requirements associated with the item;
- to consider any impact on the environment;
- to uphold the durability of the item and/or the quality of the product or service provided, considering costs.

Therefore, it is up to the distribution system operators (DSOs) to determine which (mix of) maintenance types or strategies to manage their electrical equipment best while meeting customers' requirements, regulators and other stakeholders following the ISO 55000 standard. One of the main goals for DSOs is to find the optimal balance between preventive and corrective maintenance to achieve maximum electrical equipment performance with minimum life cycle costs and optimized maintenance activities. They have to decide whether or not to perform diagnostic and/or preventive maintenance [19].

Figure 2 gives an overview of EN 13306 standard of maintenance types and, thus, selection options for DSOs in terms of maintenance strategies.

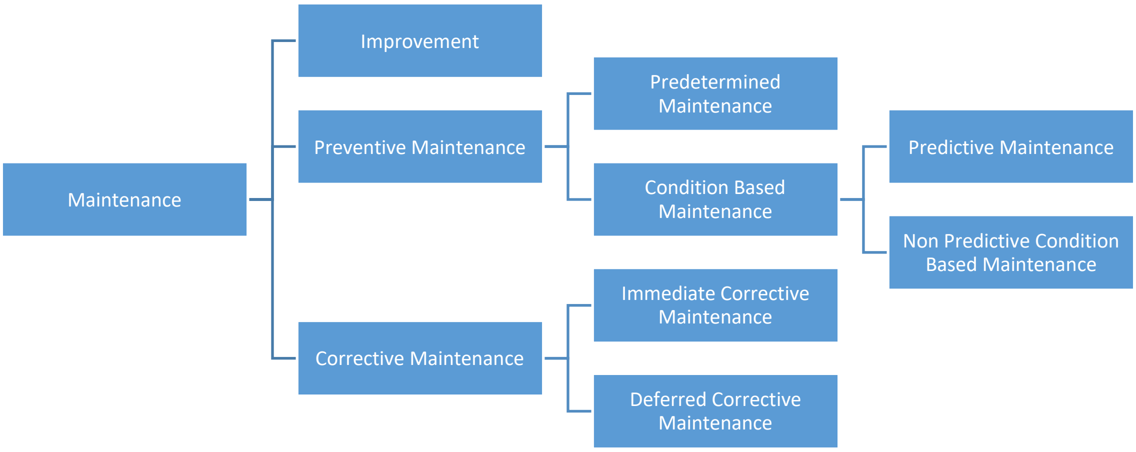


Figure 2: Maintenance types [18]

On the one hand, the reliable assessment of the technical condition of components is a prerequisite for implementing condition-based maintenance strategies. On the other hand, it also forms the basis for applying system- and risk-oriented maintenance. Table 2 [20] presents some criteria that are decisive for maintenance measures or activities of different strategies.

Table 2: Maintenance measures of different strategies [20]

			Measure			
			Inspection	**Servicing**	**Repair**	**Renewal**
Maintenance strategy	Component-based	**Corrective**	-	-	in case of outage	In case of outage
		Time-based	according to interval	according to interval	in case of outage	according to interval
		Condition-based	cycling or continuous (monitoring)	according to condition	in case of outage	according to condition
	System-orientated	**Reliability-centered**	“strategies overall process“ considering the importance of the network components to system reliability			
		Risk-based	cycling or continuous (monitoring)	according to condition, importance and outage risk	in case of outage	according to condition, importance and outage risk

The selected maintenance strategy can differ depending on the equipment group and network level. It is based on the technical, economic, legal and safety-related requirements.

Implementing a condition and reliability-oriented maintenance strategy requires a reliable recording and evaluation of the system conditions, their comparison with historical data, and the recording and ongoing updating of these systems' importance, reliability and failure potential.

The condition of electrical equipment as a function of service life and maintenance strategy - assuming a possible bathtub curve - is shown in Figure 3 as an example [21].

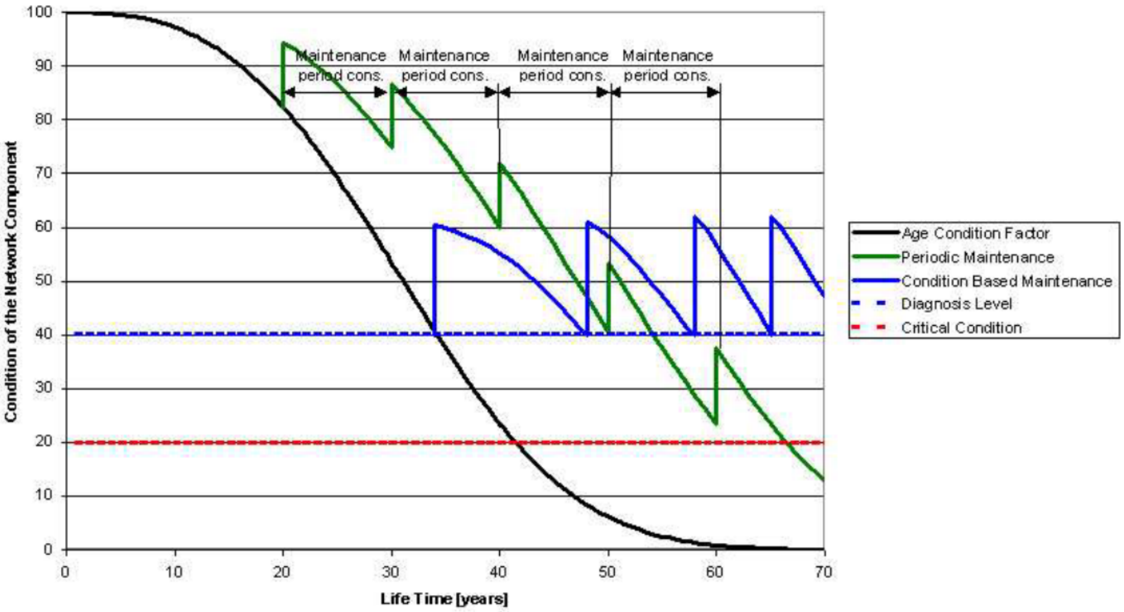


Figure 3: Maintenance strategies and their impact on the condition of the network component [21]

The black line shows the service life curve of electrical equipment based on an operating time of 40-60 years (without maintenance).

Suppose a periodic maintenance strategy (TBM, time-based maintenance, "interval-dependent", or "preventive strategy") is used. In that case, a maintenance activity is carried out regularly, as shown by the green line in Figure 3. The condition is increased by 15% each time in the example shown. Depending on the length of the interval, the condition will decline at a correspondingly slower rate, and the lifespan will be higher than 60 years. This strategy defines the cycles so that the maintenance measures and renewal occur before a possible equipment failure.

With **event-oriented maintenance** (CM, corrective maintenance, "failure strategy"), replacement or repair is carried out exclusively after equipment failure. If the consequential costs of a fault are negligible, this strategy leads to the lowest maintenance costs.

In the case of **condition-based maintenance** (CBM), a maintenance or diagnosis level (blue dashed line) must be defined. If the condition reaches this value, a maintenance action must be initiated to raise the condition again, as shown in the blue line. With this maintenance strategy, the status assessment ("diagnostics") through inspection is particularly important.

Reliability-cent**red maintenance** (RCM) is based on the fact that, in addition to the technical condition, the importance of electrical equipment and risk considerations are also considered when determining maintenance measures, as described in Chapter 3.1. The scope of equipment failures is weighted with the amount of energy not supplied and other risks.

There is also the option of **not doing any maintenance activities**. Instead, a general overhaul of the system only takes place after a certain period of use. With the general renovation (or partial renewal), the system's condition can be brought close to the new condition (brown curve), and this part can extend the lifetime curve.

However, it is crucial for all strategies to reach the critical state (red dashed line) as late as possible with the least effort and costs. Determining the degree of maintenance and the critical condition requires much operating experience and knowledge of the respective component. A risk assessment is required to determine how far these two values can be reduced. The importance of these components in the company's success and the effects of supply interruptions on customers must also be included.
The subchapters will illustrate the wide range covered by the maintenance strategies mentioned above. Firstly, the implementation of two very different strategies, Reliability Centered Maintenance and Corrective Maintenance, are discussed. Afterwards, frame conditions for modernization and retrofitting are explained. Finally, the ecological awareness and possible effects on equipment solutions are highlighted.

3.1 Reliability Centered Maintenance (RCM)

The Reliability Centered Maintenance (RCM) method is a structured approach that focuses on reliability aspects when determining maintenance plans. The concept of RCM was established in 1978 by Nowlan and Heap. They were active in the commercial aviation industry. The driving factor behind this work was improving reliability while containing the maintenance cost.

Maintenance and reliability are important because of the large costs associated with maintenance tasks and costs due to the loss of production and breakdowns. Breakdowns can also lead to consequences that affect the environment or personal safety.

This method requires maintenance plans and leads to a systematic maintenance effort. Central to this approach is identifying the items significant for system function. The aim is to achieve cost effectiveness by controlling maintenance performance, which implies a trade-off between corrective and preventive maintenance and optimal methods. The figure below gives an overview of the steps of the RCM process [22].

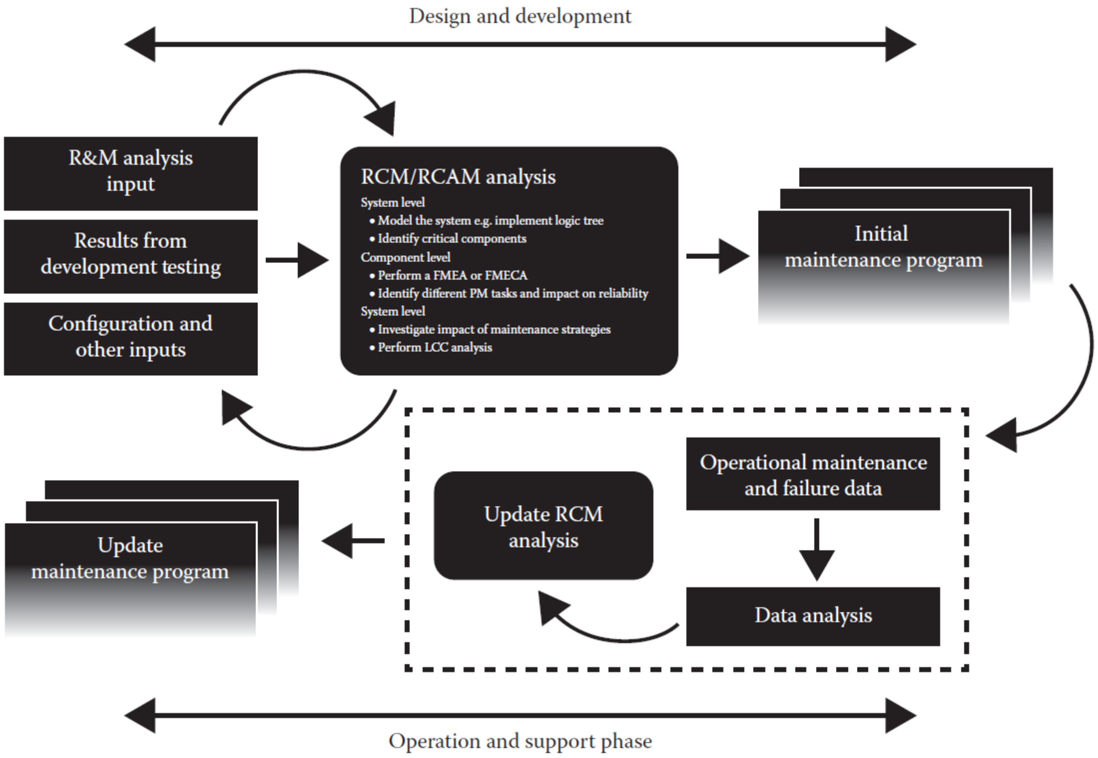


Figure 4. An overview of the steps of the RCM process [2]

a) *Simple Approach of RCM*

RCM combines preventive and corrective maintenance practices and strategies to maximize the lifetime and function of assets/systems/equipment with minimum costs. In the context of RCM, there are multiple maintenance disciplines that, if used in concert, will optimize system performance while minimizing maintenance costs. These are preventive maintenance actions and corrective maintenance.

Preventive and corrective maintenance actions are taken to preserve functionality, reduce unplanned downtime, and minimize impacts on mission performance. By their nature, preventive maintenance requires investment in activities beyond simple corrective maintenance such as inspecting, monitoring, refurbishing, or replacing.

An organization can build the best RCM program by analyzing each component's statistical performance and failure parameters, identifying important failure precursors indicators, and setting up inspection or sensor regimes to monitor for those precursor signs in crucial components.

Corrective maintenance refers to operations that are carried out to correct and fix malfunctioning systems and equipment. Corrective maintenance is used to repair systems that have broken down.

b) Advanced Approach of RCAM

Reliability-centred asset maintenance (RCAM) merges the proven systematic approach of RCM with quantitative maintenance optimization techniques (described, e.g. by [2]). While sole RCM as a qualitative method is limited in assessing the cost-effectiveness of different maintenance strategies, mathematical maintenance optimization techniques alone do not ensure that the maintenance efforts address the most relevant components and failures. By combining these two approaches, the RCAM method, originally developed for the application to electric power distribution systems, has been shown as a promising framework for the maintenance strategy selection and optimization of wind turbines [2].

As the basic part of the smart network, the equipment condition monitoring tends to be more and more intelligent based on a large amount of measurement data as input. The condition monitoring system features intelligent data storage and data analysis. The case study in Chapter 5.4 shows an example of input in an RCAM study. Classification methods with standardized categories are typically preferred to interpret measurement data to identify different failure modes [23]. In some cases, due to the lack of labels, regression models could be utilized to model normal behaviour [24]. Furthermore, deep learning models are applied to model operational data of electrical equipment with the data volume gradually increasing, like recurrent neural networks [25], etc. Based on the analysis results, health indices are proposed to prioritize the equipment's condition status and determine the corresponding preventive maintenance, replacement and refurbishment [26].

3.2 Reasonability of Corrective Maintenance

Corrective maintenance is based on intervening only in case of failure or outage. The repair or replacement must be done quickly to meet the network's quality or redundancy requirements. On the other hand, maintenance costs are decreased. This strategy is economical as long as the effort for additional repair or replacement and overall outage costs are lower than the costs for maintenance actions. However, several aspects have to be considered for this decision.

Without maintenance and inspection, estimating the electrical equipment's condition is impossible. If failure leads to, e.g., a smaller repair, it is almost impossible to estimate the lifetime of other/depending parts of the equipment. Therefore, a database decision, if repair is more economical than replacing electrical equipment, is nearly impossible. The repair or replacement hereafter might need specialized spare parts. To meet the requirements concerning outage time, they should be available in the short term. But without information about the condition, there is no indication of which spare part might be interesting. Online monitoring solutions or a regular condition assessment approach where the required information can be collected in the field can help enlarge the pre-warning time and give first indications of failure mode.

Another risk of this strategy is an accepted overall ageing of network equipment. This strategy leads to a very poor plannability of investments and high risk on unplanned budget peaks because external failures mainly drive them. Due to the overall ageing, the risk of chain reactions on external incidents (e.g., overvoltage-incidents, earth faults etc.) on the gird equipment is rising.

Independent of the maintenance strategy, the costs for replacement will not change significantly. Only the timeline will be different. In corrective maintenance, maintenance actions are omitted, which helps keep the equipment in good condition. Therefore, the failure rate is presumably higher compared to predictive maintenance methods. The costs and effort of human resources for repair or replacement rise with the failure rate. Furthermore, unpredictable assignments are difficult to schedule for the asset manager and the personnel. Still, it can be reasonable if all efforts are counterbalanced.

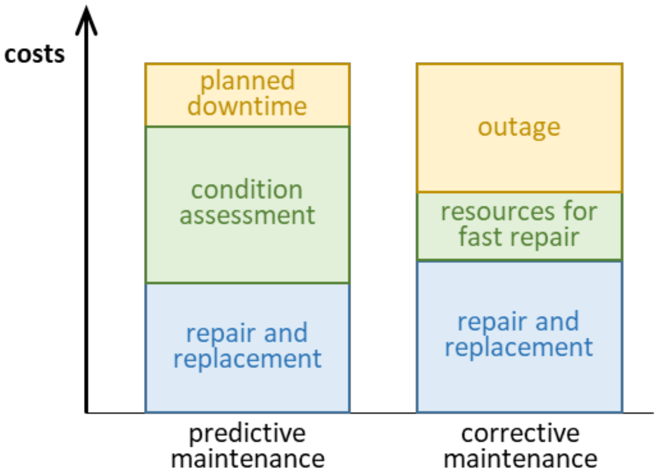


Figure 5 Illustration of qualitative cost relations for predictive and corrective maintenance strategies

Besides these challenges, the financial efforts must be considered, as illustrated in Figure 5. It results from the direct replacement or repair costs, the costs for the maintenance action and the costs of downtime/outage:

- The costs for a replacement or repair after a failure will stay roughly constant, even though the occurrence is probably increasing.
- The resources for a fast repair (e.g., workforce and spare parts) cannot be saved because they are needed in the case of failure.
- The costs for predictive maintenance are higher than for corrective strategy. Here, only in case of a failure a maintenance action is done.
- Cyclic inspections generate the data needed for a reliable asset strategy and financial planning or risk management.
- The outage costs strongly depend on the failure rate of the equipment. By nature, it is higher for corrective maintenance. It can consist of lost network charges, costs for short-time substitutes or additional penalties.

The actual costs, as mentioned above, have to be calculated individually. The outcome is quite different depending on voltage level, equipment type, fleet age, etc.

The following example illustrates the outage costs for distribution networks in Germany. In German distribution networks, the 110 kV network is (n-1) redundant so that no outage is to occur. The system always covers failures in a single component. However, medium and low-voltage networks tolerate a small outage time. Within this outage time, the network charges are lost. Furthermore, installing a short substitute to decrease outage time might be necessary, which leads to the additional financial effort. Lastly, an outage penalty by the regulator is accounted for.

The ***outage penalty*** for low voltage depends on the number of connected but not supplied end customers n_{out}, the outage time t_{out} and specific outage costs c_{costs}, which range roughly between 0.2 … $0.4€/min$:

$$C_{LV[€]} = n_{out} \cdot c_{costs[€/min]} \cdot t_{out[min]}$$

For medium voltage, the penalty is additionally depending on not supplied transformer power $S_{tran,out}$ related to the overall connected transformer power $S_{tran,total}$.

$$C_{MV[€]} = \frac{S_{tran,out\ [MVA]}}{S_{tran,total\ [MVA]}} \cdot n_{total} \cdot c_{costs[€/min]} \cdot t_{out[min]}$$

The case of a planned outage is weighted by a factor of 0.5, indicating less severity because the end customer can schedule it.

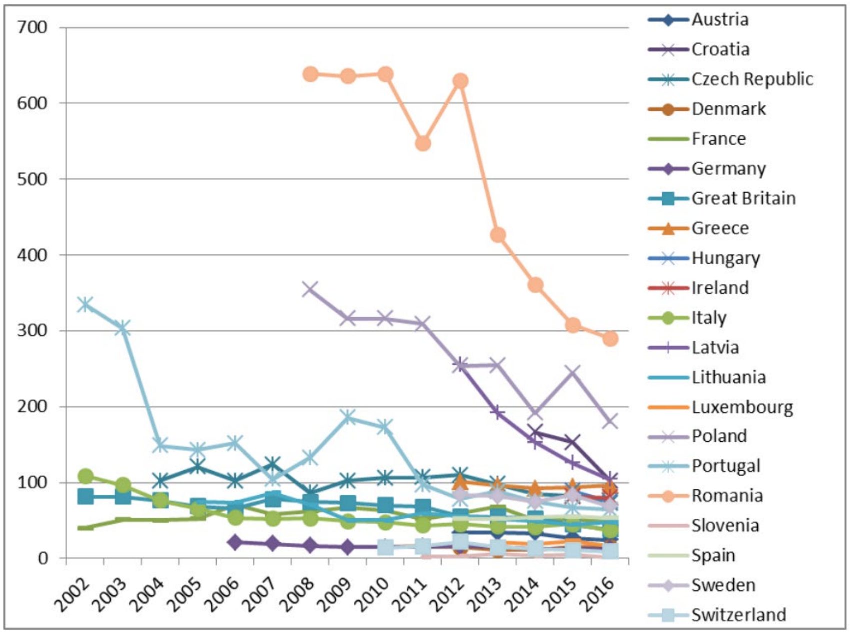


Figure 6 Unplanned SAIDI of European countries, without exceptional events (minutes per customer) from [27]

Two measures exist to indicate the average sum of outage times:

SAIDI (System Average Interruption Duration Index)
Is the average supply interruption per connected end consumer within a calendar year. An overview of European countries for the years 2002-2016 is shown in Figure 6.

$$SAIDI = \frac{\sum n_{out,i} \cdot t_{out,i[min]}}{n_{total}}$$

ASIDI (Average System Interruption Duration Index)
Is the average interruption time of supply per connected rated power within a calendar year.

$$ASIDI = \frac{\sum S_{tran,out,i\ [MVA]} \cdot t_{out,i[min]}}{S_{tran,total\ [MVA]}}$$

These values can be used for the calculation of the penalties:

$$C_{LV[€]} = SAIDI \cdot n_{total} \cdot c_{costs}$$

$$C_{MV[€]} = ASIDI \cdot n_{total} \cdot c_{costs}$$

In Germany, a SAIDI of 2.4 minutes in a low-voltage network and an ASIDI of 10.3 minutes in a medium-voltage network occurred in 2021 [28]. The specific cost is estimated to $c_{costs} = 0.2\ €/min$. For a distribution network with $n_{total} = 100\ 000$ connected end customers, the penalties can be estimated to:

$$C_{LV} = SAIDI \cdot n_{total} \cdot c_{costs} = 2.4min \cdot 100\ 000 \cdot 0{,}2\frac{€}{min} = 48\ 000€$$

$$C_{MV} = ASIDI \cdot n_{total} \cdot c_{costs} = 10.3min \cdot 100\ 000 \cdot 0{,}2\frac{€}{min} = 206\ 000€$$

As the number of magnitudes for the penalties indicates, saving maintenance costs and relying on a corrective strategy might be economical. Cost savings might be won in the short term. However, as the points above describe, the overall condition of the network components will worsen. Long-term effects are difficult to predict, and there is a risk of not meeting the network's future quality or redundancy requirements.

3.3 Modernization and Retrofitting

Modernization and retrofitting methods include physical interventions, which directly change major components to maintain or even upgrade the reliability and expected performances of the electrical equipment in time, e.g. the insulation material of existing equipment. Case studies concerning this matter are given in [29]. Different modernization strategies can be applied to, for example, medium voltage switchgear, enabling equipment upgrade considering constraints in place, such as budget requirements and impact on the process.

a) Refurbishment

Refurbishment is looking for a short to medium-term life extension of electrical equipment to preserve the original level of reliability. This solution requires returning the equipment to the manufacturer. Therefore it depends on the availability of spare units on site to keep the full plant operational while it applies to limited batches on a rotational basis. When returned to the manufacturer, the equipment is disassembled and checked for worn parts that are replaced, goes through a routine test sequence, and leaves the factory covered by a new warranty period. A refurbishment is a viable option for active products or products for the original manufacturer that still provides the main parts.

b) Replacement

Original switchgear replacement with a brand new one is at the opposite end of the modernization strategy portfolio; it provides the highest benefit regarding functionality upgrade to state-of-the-art technology and long-term parts availability, aligning the electrical equipment to the latest international standard. While technically, replacement may be the best option for long-term reliability, and it is often not the chosen solution for several reasons: highest capital expenditure that may not match the supplied process business plan or operational life expectations, physical constraints of the existing site, impact on system boundaries, such as cables and cable terminations, cannot be executed in steps to take in consideration budget or operational priorities; long downtime required for dismantling and to install is not process acceptable.

c) Roll-in Replacement

Roll-in Replacement (RiR) solutions are one-to-one engineered unit exchanges to the original device. It replicates all interfaces to the panel, providing a higher degree of renovation and higher reliability. This solution requires a deep knowledge of the original design and interface to panel operation to ensure the new units are interchangeable with the original ones. There is no limit on the number of units that can be replaced, and the full line-up can be updated in one batch or as required by operational priorities.

When a retrofit design is developed, type testing according to the latest standards to verify ratings and ensure the safe operation of all expected interlocks is a key requirement.

d) Retrofit

Retrofill is a switchgear modernization process that includes the replacement of the original circuit breaker with a standard withdrawable circuit breaker by installing a fixed frame that provides the new circuit breaker interface in the existing switchgear.

Such a solution is applicable when the existing switchgear is in serviceable condition. It can greatly upgrade the switchgear safety performances as it replaces many of the original panel parts, like the shutter and shutter operation system and all relevant interlocks, in addition to the circuit breaker.

Retrofill requires a longer bus outage when compared to RiR direct replacement due to the original switchgear cell modifications needed to accept the hosting frame and new circuit breaker.

Each of the modernization solutions described has pros and cons and can be the best suited for a specific case depending on original design, condition, expected lifetime extension target and other factors. To provide a first-level evaluation, Figure 7 below shows a qualitative comparison of the different modernization solutions regarding technical features.

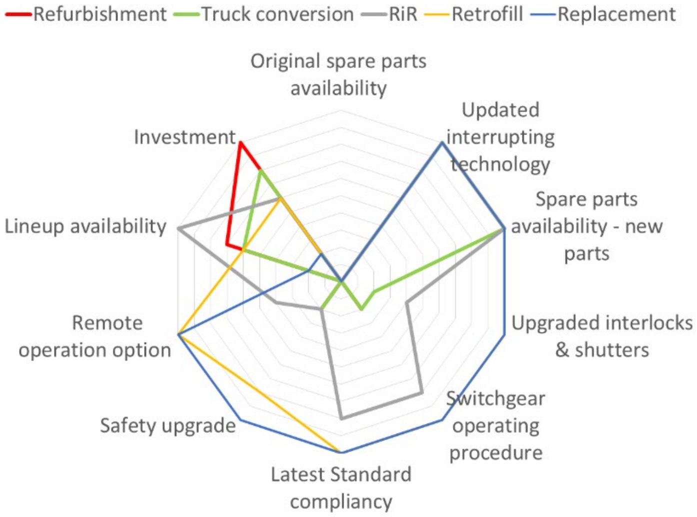


Figure 7 Qualitative comparison of modernization, the length of radius indicates the effect on the aspect

Figure 8 compares direct costs and effort associated with the two major modernization alternatives, replacement versus retrofit.
The two solutions' most obvious material purchasing price is often comparable. At the same time, added costs for the civil works and installation and commissioning phase may lead to significant differences in the solution's total cost. Switchgear replacement area/effort (in orange) on most parameters is larger than the retrofit modernization footprint. It means that modernization is less time and resources consuming than replacement. Field technician’s mobilizations represent the costs associated with technician time on site, such as travel, lodging, etc. Installation materials and tools are relevant to consumable, special installation tools and material-movement equipment needed at the site.
Revenues losses due to modernization shutdown time are strongly dependent on process and industry and on the original network available redundancy. This element can tip off the decision for a faster or less invasive modernization solution.

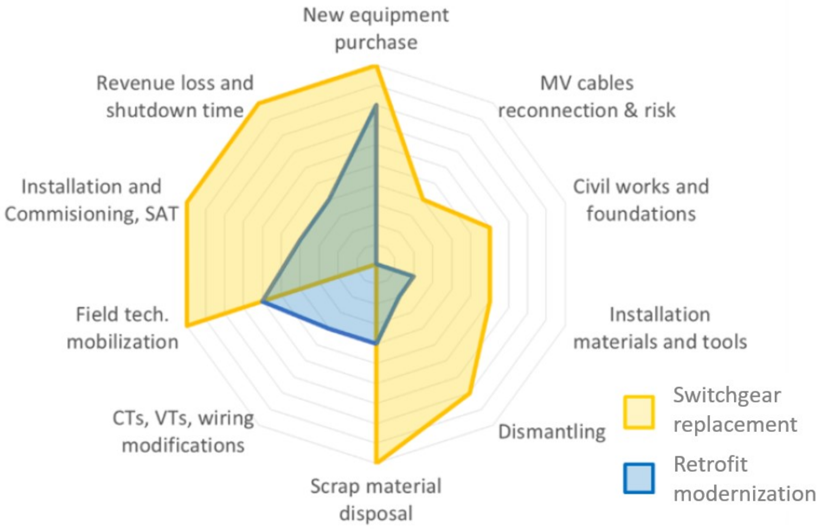


Figure 8 Qualitative comparison of modernization cost-effort, the length of radius indicates the effect on the aspect

IEEE C37.59 standard covers power switchgear equipment converted from a qualified design (any power switchgear equipment tested and certified to appropriate industry standards).
It provides direction and guidance in conversions and specifies required design verification through design testing and/or evaluation, supported by justified technical evaluation, following applicable IEEE standards. It refers to standards in effect when equipment manufacture and converted equipment shall continue to meet the original ratings.

In the IEC world, there is no specific standard covering conversion solutions. Those are labelled according to new equipment standards IEC62271-100, -200 and shall accordingly be type tested. The applicable reference for design evaluation is TR IEC 62271-307. It defines the criteria and guides the validity extension of type tests of MV equipment.
The fundamental philosophy underlying both IEEE and IEC standards is that a converted (retrofit) product shall substantiate that it meets its nameplate ratings and applicable standards. Conversion solutions shall be tested in their applicable switchgear enclosures.

3.4 Circular Economy Aspects

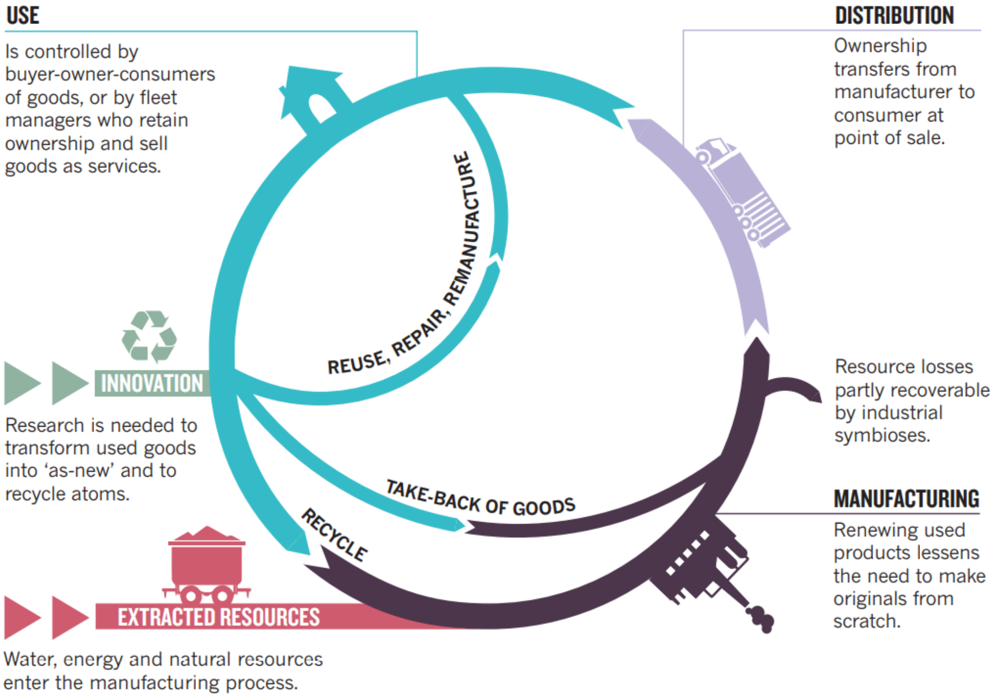


Figure 9 Illustration (from [30]) of the basic idea for circular economy

The acceleration of socioeconomic activities has led to intense resource usage and emissions expansion into the earth system. As a possible solution, the circular economy is proposed as an advanced production and consumption system that may lead society towards sustainable development. The circular economy is based on the 5R rule, "rethink, reduce, reuse, repair, recycle", and its objective is to reduce the depletion of natural resources. Shifting from the traditional "take, make, consume, and throw away" economic model to a zero-waste, circular economy focuses on making more intelligent decisions to use the resource to their maximum capacity. The circular economy model designs long-lasting products for electrical power systems that can be refurbished, repaired, reused, and upgraded. It retrofits equipment to prolong its lifespan and minimize the environmental impact instead of directly replacing them.

In 2015, the European Commission adopted an ambitious Circular Economy Action Plan (CEAP), which includes measures to help stimulate Europe's transition towards a circular economy, boost global competitiveness, foster sustainable economic growth and generate new jobs.
The EU Action Plan for the Circular Economy establishes a concrete and ambitious program of action, with measures covering the whole cycle: from production and consumption to waste management and the market for secondary raw materials and a revised legislative proposal on waste. The proposed actions will contribute to "closing the loop" of product lifecycles through greater recycling and reuse, benefiting the environment and the economy.
On March 11, 2020, the European Commission established a new Circular Economy Action Plan (CEAP) under the roof of the "European Green Deal". [31]

The plan addresses many items (a total of 35), and among them, the list below is interesting for lifetime extension of electrical equipment:

- the creation of a European Dataspace for Smart Circular Applications in synergy with existing databases such as SCIP ("Substances of Concern In articles as such or in complex Products");
- a European “right to repair” focusing on electronics and ICT (Information & Communication Technologies) products;
- a legislative proposal on the use of Product and Organizational Environmental Footprint;
- aligning the waste legislation framework to promote waste prevention, separation and circularity;
- targeting electronics, batteries, packaging, plastics, in particular microplastics, textiles, construction, food and water;
- facilitating the circulation of safe and high-quality secondary raw materials, e.g. via standardization and further restrictions, e.g. on POP (persistent organic pollutants) substances and supporting sorting and decontamination;
- posing restrictions on SVHC (Substances of Very High Concern) in addition to authorization to avoid SVHC in imported products;
- introducing taxation rules and accounting principles concerning environmental issues.

4 Condition assessment

As explained in Chapter 3, responsible asset managers seek a high-reliability level with a simultaneous increase in service life and compliance with the given financial framework. The prerequisite for compliance with these goals is a good knowledge of the technical condition of the entire fleet and the individual equipment. In this way, those responsible can make short-term and long-term decisions regarding the renewal and maintenance strategy of the individual units. In case any spare parts are used, their quality and condition must be ensured. So, the condition assessment should also involve spare parts, as the case study in Chapter 5.7 indicates. Various diagnostic options and methods exist to assess the condition of single equipment or a whole fleet. Components or parts can be assessed, and thresholds defined based on the results. For larger systems comprising several components, such as power transformers or switchgear, the results often are aggregated to provide information about the condition in the form of a single value (often known as a "health index"). In many cases, the result is not specific enough for the individual stakeholder because in most companies' different groups are responsible for optimal fleet management from different perspectives:

a) operational and rather operating cost-oriented (OPEX) and
b) focused strategically and more on capital expenditures (CAPEX).

Fleet management approaches could directly address these different groups within the company by using two indices directed to the responsible decision-makers for CAPEX and OPEX questions and enable overall optimization. An application example is given in the case study in Chapter 5.2.

4.1 Strategic Focus and Challenges of Condition Assessment

In the past, DSOs almost exclusively used time-oriented or cyclically-oriented maintenance strategies and electrical equipment was mostly replaced based on their operating lifetime [32]. To make optimum use of the limited financial resources available while at the same time maintaining the reliability of supply of the distribution network and taking legal requirements into account, maintenance and replacement strategies have become increasingly important and sophisticated. Thus, DSOs are permanently searching for optimization opportunities, with targeted maintenance and replacement planning becoming their focus. All strategies have one thing in common: they are only as good as the basis on which they are built. That is the most accurate possible condition assessment of the electrical equipment under consideration [33]. Only an objective and realistic condition assessment can provide a sound basis for asset management decisions [33]. Statistical analysis of past failures helps to identify weaknesses and find appropriate diagnostic methods for a reliable condition assessment, as shown in the case study in Chapter 5.5.

The approach to condition assessment can thus be divided into two different perspectives: replacement – long-term perspective – and maintenance – short-term perspective [34]. The condition assessment should take these different perspectives into account. Replacement planning is mainly relevant for asset management, while maintenance planning is more relevant for asset service. The applied approach to condition assessment should support both perspectives. However, different time and financial factors are also relevant for the different perspectives. Asset service must address a missing warning sign immediately but does not influence asset management policies in the context of replacement decisions. However, deterioration due to ageing shortens the lifetime of the affected electrical equipment and is very relevant for asset management in the context of replacement decisions. The contents of the

condition assessment should also be understandable and transparent, i.e. only inspection issues that assess the technical condition of the electrical equipment are used at first. Other issues, such as the availability of spare parts or financial factors, should be considered separately.
The requirements for a condition assessment and the economically justified effort strongly depend on the voltage level [32]. It must be weighed up how complex a condition assessment may be and which requirements must be considered. In the high-voltage and extra-high-voltage network, each item of equipment has a considerable individual value. Here, a more complex condition assessment of the individual equipment is justified, which also includes the use of extensive measurement methods. In the medium and low-voltage networks, the value is considerably smaller. Therefore, the condition assessment methods are limited in the effort, and inspection methods are of higher importance.

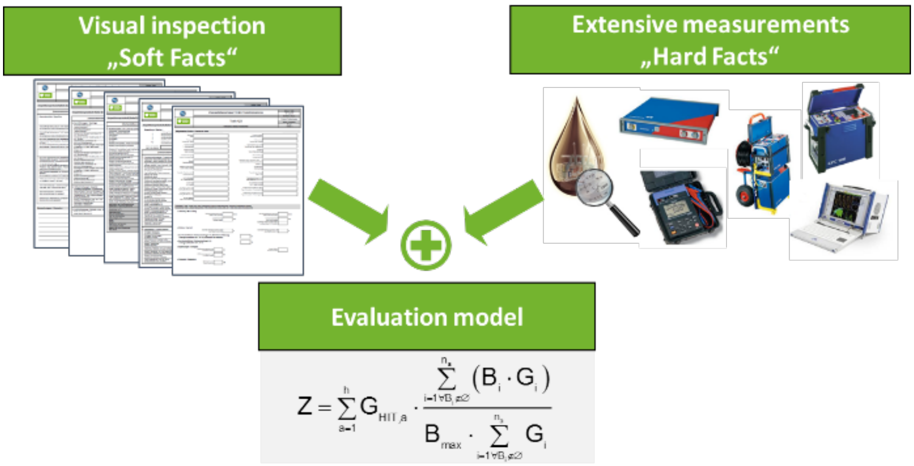
4.2 Implementation Using the Example of Power Transformers

a) Inspections for data acquisition

DIN VDE 0105-100 prescribes the performance of routine tests intended to assess the proper condition of electrical components [32]. Since regular inspections of electrical equipment are thus mandatory, they provide a suitable data basis for condition assessment. Moreover, visual inspection is the foundation of successful maintenance and a simple way to obtain the information relevant to operation and to detect the existing defects of the equipment and its components [33]. The visual inspection uses an inspection checklist developed specifically for transformers [35].

b) Evaluation model

Figure 10 shows an example process which can be used for the determination of the overall condition index of a transformer in a simplified form.



$$Z=\sum_{a=1}^{h} G_{HIT,a}\cdot\frac{\sum_{i=1\forall B_i\neq\emptyset}^{n_a}(B_i\cdot G_i)}{B_{max}\cdot\sum_{i=1\forall B_i\neq\emptyset}^{n_a} G_i}$$

Figure 10 The basic principle of the condition assessment model [35]

The use of measurement methods provides concrete measurement results (“hard facts”) that selectively expand the purely visual inspection of the maintenance personnel (“soft facts”) [35]. The electrical components can be subjected to a well-founded and realistic condition assessment through visual inspection and measurements. The experience of the maintenance personnel can reveal visual defects that cannot be detected by the measuring instruments (e.g. developing leaks, rust, etc.). Conversely, conditions in the insulation (e.g. moisture in oil) can only be identified via the measurement methods used because no visual damage can be detected. The assessment methods complement each other and, in combination, provide a well-founded and realistic condition assessment.

An aggregated overall index of the condition makes it possible to classify and prioritize transformers for optimized asset strategies. To take into account the different perspectives – maintenance and replacement – in the context of condition assessment, the following two indices are determined [35]:

- Lifetime consumption index
- Failure risk index

The failure risk index mainly considers the short-term maintenance measures that must be carried out. Thus, defects may increase the failure risk despite an overall good condition but can be eliminated with little effort and operative expenditures (OPEX). In contrast, the lifetime consumption index considers the transformer's long-term operation. Here, replacement- and lifetime extension-related aspects and input data that indicate a lifetime shortening are considered. The developed condition assessment model has been tested in practice by various DSOs [35] [36].

c) Uncertainty of condition assessment

The condition assessment results based on visual inspections can show a high subjectivity [33]. Although a uniform inspection checklist and a suitable weighting procedure are used as part of the condition assessment, the assessments of the maintenance personnel do not always match, as the different assessment results are based on the individual wealth of experience of the maintenance personnel. The results are thus only comparable to a limited extent due to different approaches and evaluation precepts of the maintenance personnel [32]. Although a systematic approach and evaluation are adopted to reduce subjectivity, the influence of individual experiences and preferences of maintenance personnel is still present. As a result, measures must be taken to create an optimized decision-making basis for asset management [33].

Maintenance personnel should be intensively trained to standardize their evaluation bases to increase the comparability of results. In addition, a reference catalogue can be used to classify the identified deficiencies better. A further reduction of the subjective influence and increased significance are achieved using different measurement methods [37].

d) Accuracy and detection potential of measurement methods

For a precise, reliable and objective assessment of the technical condition of a transformer and for the early detection of faults that could lead to a failure, the visual inspection must be supplemented through suitable measuring methods. Appropriate measurement methods for this purpose already exist. An overview of the potentially applicable measurement methods can be found in [35], among others, although these methods usually require a high level of effort in their application. A condition assessment and an assessment of the existing maintenance requirement can be made based on various measurement methods and the obtained measured values. However, the measurement methods' detection capability must also be considered. The detection capability generally results from considering the sensitivity of the method to detect a defect (detection potential) and from measurement deviations in multiple measurements (accuracy of the method) [37].

e) Dealing with data quality

The input data that can be included in the condition assessment of transformers has varying objectivity and informative value. However, they significantly determine the reliability of the condition assessment. Here, the reliability depends on the quantity and quality of the underlying input data. In asset management, decisions must be made under uncertainty since complete and absolute reliable information is seldom available [33]. For example, the quality of the condition assessment is influenced by the number of inspection points assessed.

In addition to missing input data, the time the input data is collected also influences the quality of the resulting condition assessment [33]. Inspections of electrical equipment and oil analyses are conducted in a cyclical rhythm, whereby sometimes the cycle lasts several years. Such an outdated evaluation result has not the same informative value or credibility as a current evaluation result. In addition, various operational stresses and environmental influences may have affected the equipment or oil, necessitating maintenance. Therefore, the age of the input data should be taken into account.

The evaluation models were developed for this purpose, for example, based on the mathematical principles of evidence theory to process uncertain, incomplete or outdated information and quantify its informative value. As a result, asset management is not only provided with a condition index for the transformer, but the associated uncertainty range of this assessment is also modelled. The size of the resulting uncertainty range expresses the reliability of the condition index and, thus, the quality of the condition assessment. In the case of a very uncertain condition assessment, there is the additional option, depending on the willingness to take risks, of either tolerating the uncertainty and making a decision or initiating the collection of further information [35] [36]. It means a considerable information gain for the condition assessment of transformers since uncertain condition assessments are evidenced and will prevent wrong decisions based on an apparent condition. The uncertainty is thus an important additional parameter for maintenance and replacement decisions.

4.3 Diagnostic and Inspection Methods

The following chapter outlines applicable diagnostic and inspection methods for electrical equipment and related detectable errors and failures. For further details, literature references are given.

4.3.1 Oil-Filled Power Transformers

The content of this subchapter has mainly been adopted from [5], which provides a very wide description of the ageing effects of oil-filled power transformers and shunt reactors. It has been adapted to fit the structure and content of this brochure. For more information on this topic, refer to [5]. However, as the CIGRE focuses on higher voltage levels, not all mentioned methods are commonly used for distribution transformers.

An oil-filled power transformer consists of many parts and components which are more or less prone to ageing. The main aspects of ageing are degradation of the solid and liquid insulation affecting dielectric, mechanical and geometric properties, and contact wear. Insulation ageing starts during insulation production and can never be completely avoided. Therefore, slowing down the degradation rate is the objective of transformer life extension.

To give a clear view of such a complex system, the diagnostic and inspection methods are grouped into four subdivisions relating to the main parts of the transformer: active part, bushings, tank (including cooling) and tap changer. The following tables overview common ageing effects, deviations and failures, and related detection methods. The methods are categorized into electric, electric advanced, dielectric, chemical and oil analysis as well as other methods. Suitable methods are marked with an “X”, methods which might be suitable in some cases or are less efficient are marked with an “O”; not recommended or improper methods are left blank. Even if a method is applicable and does not detect an error or failure, it does not guarantee any such error or failure. The method simply might not be able to detect it. To overcome this uncertainty, several methods are usually combined to produce a qualified result. The condition of the **active part** is of high importance, as half of the failures in high-voltage power transformers are located here [38]. The following Table 3 and Table 4 give an overview.

Table 3: Detection methods for active part–winding and main insulation (adapted from [5]; X-suitable, O-possible, but less efficient)

	major component		winding / conductor												main		
	sub component		winding / conductor								Insulation	shielding elements		press construction	insulation		
	method	failure	turn-turn fault	coil-coil fault	coil-ground fault	lead-lead fault	lead-ground fault	mechanical deformation	short circuit between parallel strands	contact problem	insulation breakdown	floating potential	short circuit	Loss of claming force	moisture	corrosive sulphur	low DP
electric	turns ratio		X	O	X	X	X				X						
	insulation resistance				X	X					X				O		
	winding resistance		X	O		X				X	X						
	exciting current		X										X				
	short-circuit impedance		X	X				X	X								
	induced voltage		X	X	X	X					X						
	applied voltage				X						X						
electric advanced	dynamic resistance		X							X	X						
	FRSL								X								
	FRA		X	X	X	X	X	X		X	X	X					
	PD analysis		X	X	X	X	X				X	X	X				
dielectric	capacitance and dielectric loss				X	X					X	X			O		
	dielectric response analysis (FDS, PDC)				X	X					X	X			X		
chemical and oil analysis	DGA		X	X	X	X	X		X	X	X	X	X				
	BV, color, IFT sediments, sludge, …																
	moisture in oil														X		
	conductivity, dielectric loss																
	acidity																O
	particle analysis		X								X	O	X				
	furan analysis																X
	corrosive sulphur analysis															X	
other	external inspection																
	internal component inspection													X			
	functional tests																
	alarms																
	fault recorder			X	X	X	X				X						
	thermovision																
	winding temperature		X						X								
	core temperature																
	CT tests																
	vibration and acoustic analysis													O			

Table 4: Detection methods for active part – core, oil and oil preservation system, internal components (adapted from [5]; X-suitable, O-possible, but less efficient)

	major component	core							oil and oil preservation system						internal components									
	sub component	core steel/ laminates / sheets			insulation & connection to tank		core frame		oil						capacitors		inductors			over voltage protection			Jumper connections	CTs for measurement and protection
	failure	lamination insulation breakdown	moving sheets	core steel joint opening	insulation breakdown (double grounding)	core ground open	Insulation breakdown between core and frame or frame and frame parts	broken frame or components, missing shielding elements	moisture intrusion	particles	sluge and X-wax formation	corrosive sulphur	high oil conductivity	oxidation	open circuit	short circuit	winding failure	deformation	open circuit	short circuit	degradation, partly damaged	open circuit	contact problems	functionality (ratio, kneepoint, insulation, wiring, …)
	method																							
electric	turns ratio															X							O*2	
	insulation resistance				X*1		O*1						O							X				
	winding resistance															X	O		X				X	
	exciting current	X		X	X		X														X			
	short-circuit impedance																X	X	O					
	induced voltage																							
	applied voltage																							
electric advanced	dynamic resistance																							
	FRSL																							
	FRA	O		O		X	X										X	X	X				X	
	PD analysis	X	O			X	O	X							X	X	O		X				X	
dielectric	capacitance and dielectric loss				X*1	X*1			O		X		O							X				
	dielectric response analysis (FDS, PDC)				X*1	X*1			O		X		X	X						X				
chemical and oil analysis	DGA	X	O	X	X	X	X	X			X			X	X	X	X		X		O	O	X	
	BV, color, IFT sediments, sludge, …										X			X										
	moisture in oil								X															
	conductivity, dielectric loss								X				X											
	acidity								O		X			X										
	particle analysis				X			O		X									O				O	
	furan analysis																O		X					
	corrosive sulphur analysis											X												
other	external inspection																				X	X		
	internal component inspection		X																					
	functional tests																							
	alarms							O																
	fault recorder																							
	thermovision				X																			
	winding temperature										X					O							X	
	core temperature						X				X													
	CT tests																							X
	vibration and acoustic analysis	X	X	X				O																

**1: If accessible via core ground bushing*

**2: When the difference between load and no-load situations is significant*

About a quarter of the failures on high-voltage transformers are related to **bushings** [38]. The reasons for this are manifold. They experience high electrical stress and act as a filter for overvoltage and transients. They have a small volume, prone to moisture ingress and leakage problems, compared to a high surface area, including different interfaces to air, oil and solid material. Furthermore, external influences like mechanical or thermal stresses or contaminations will affect the bushing conditions.

One common method for oil-filled components is oil analysis. In principle, it applies to oil-filled bushings. However, as the volume of bushing oil is quite small, multiple sampling might be problematic. The sampling procedure is complex, and the oil volume needs to be refilled.

Table 5: Detection methods for bushings (adapted from [5]; X-suitable, O-possible, but less efficient)

	major component	**bushing**															
	sub component	**condenser**							**drawn flexible lead of winding**	**drawn rod**		**connector bottom contact**	**outer insulation**			**plugs, calbe connection**	
	method / **failure**	**insulation breakdown**	**loss of oil**	**oil containment**	**shields not in place**	**contact problem**	**moisture ingress**	**PD caused by floating potential**	**arcs between conductor and tube**	**arcs between conductor and tube**	**overheating**	**overheating**	**polluted surface**	**cracks …**	**loss of gas pressure**	**trapped air, voids, …**	**contact problem**
electric	turns ratio																
	insulation resistance						O						X				
	winding resistance										X	X					
	exciting current																
	short-circuit impedance																
	induced voltage																
	applied voltage																
electric advanced	dynamic resistance																
	FRSL																
	FRA																
	PD analysis	O	O		X		O	X					X	X	O	X	
dielectric	capacitance and dielectric loss	X	O	O		X	X	X					X			O	
	dielectric response analysis (FDS, PDC)	X	O	O		X	X						X			O	
chemical and oil analysis	DGA	X		O	O	X		X	X*2	O		X					
	BV, color, IFT sediments, sludge, …																
	moisture in oil			O			O*1										
	conductivity, dielectric loss			O													
	acidity			O													
	particle analysis			O													
	furan analysis																
	corrosive sulphur analysis			X													
other	external inspection		X					O					X	X			
	internal component inspection																
	functional tests																
	alarms														X		
	fault recorder												X				
	thermovision	O	X				O				X		X				X
	winding temperature																
	core temperature																
	CT tests																
	vibration and acoustic analysis																

**1: Due to the usually good oil quality, the absolute moisture content in the bushing oil can be very low, even at moderate or high content in the cellulose of the active bushing part. Therefore, the relative water content (water activity AW) is more relevant than the ppm value.*

**2: Typical increase of gases will occur in the transformer oil and not in the bushing oil*

The **tank and cooling system** are not directly linked to frequent failures of power transformers [38]. But it certainly influences the temperature and water ingress and affects the ageing rate indirectly. A lower service temperature and better preservation system can increase the lifetime of a power transformer.

Table 6: Detection methods for tank and cooling system (adapted from [5]; X-suitable, O-possible, but less efficient)

	major component	oil and oil preservation system														tank							
	sub component	conservator	piping		pump			fans			radiator plates			Coolers tubesheeds	cooler case	caskets	piping	structural steel			tank not grounded	shielding elements	
	method / failure	bladder failure	incorrect valve position(s)	oil containment failure	motor failure	bearing failure	loss of power (oil flow)	motor failure	bearing failure	loss of power	weld failure	rust /corrosion	loss of power or efficiency *2	rust /corrosion	rust / corrosion	Loss of oil containment	loss of oil containment	structural failure	flux heating	corrosion, rust	tank not grounded	floating	short circuit
electric	turns ratio																						
	insulation resistance																				X		
	winding resistance																						
	exciting current																						
	short-circuit impedance																						O*3
	induced voltage																						
	applied voltage																						
electric advanced	dynamic resistance																						
	FRSL																						O
	FRA																					O	
	PD analysis																					X	
dielectric	capacitance and dielectric loss	O																					
	dielectric response analysis (FDS, PDC)	X																					
chemical and oil analysis	DGA	X																	X			X	X
	BV, color, IFT sediments, sludge, …																						
	moisture in oil	X																					
	conductivity, dielectric loss																						
	acidity	O																					
	particle analysis					X													O	O			
	furan analysis																						
	corrosive sulphur analysis																						
other	external inspection	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X	X	X	X		
	internal component inspection																						
	functional tests																						
	alarms			X*1	X		X	X		X	X		O			X	X	X					
	fault recorder																						
	thermovision		X	X	X	X	X	X	X	X			X			X	X		X				O
	winding temperature		X	X	X		X	X		X			X			X	X						
	core temperature		X	X	X		X	X		X			X			X	X						
	CT tests																						
	vibration and acoustic analysis				X	X		X	X	X													

**1: Oil level, Buchholz and pressure relays*
**2: Airflow reduction due to clogging etc.*
**3: On the resistive part*

About one-quarter of high-voltage power transformer failures are within the **tap-changer** [38]. OLTCs are especially rather complex in design and operation, which is why most of these failures are related to improper or insufficient maintenance. Some older OLTCs showed design-related issues. More recently, several failures have been related to corrosive sulphur. Contact coking may occur for DECTs when not operated for years, resulting from a resistive layer on a contact surface, possibly creating a hot spot. Moisture ingress or poor oil condition leads to insulation degradation and might also cause failures for both OLTC and DETC.

Table 7: Detection methods for tap-changer (adapted from [5]; X-suitable, O-possible, but less efficient)

	major component	deenergized tap changer (DETC)					on load tap changer (OLTC)																Motor drive					protection		
	sub component	tap selector					tap and change-over selectors						diverter / selector switch						compartment		transition impedance		linkage gears		motor control			oil surge relay	pressure relief device	over voltage protection
	failure method	contact overheating	contact coking	misalignment	silver / copper corrosion	partial discharge	contact overheating	contact coking	misalignment	silver / copper corrosion	arcing, excessive sparking	partial discharge	excessive contact wear	loose or broken parts	excessive wear, backlash	overheating	silver / copper corrosion	bad transition time	leaks to mein tank	moisture ingress	broken resistors	reactor problems	degradation: wear, rust	bad synchronism	wrong operation / indication	brake failure	motor problem	loss of functionality	loss of functionality	loss of functionality
electric	turns ratio																					O		O	O					
	insulation resistance																													
	winding resistance	X	X		O		X	X		O			O			O	O					O								
	exciting current																					X								
	short-circuit impedance																					X								
	induced voltage					X						X																		
	applied voltage					O						O																		
electric advanced	dynamic resistance						X	X					O	O	O	O		X			X	X		X						O*
	FRSL																													
	FRA																													
	PD analysis					X						X																		
dielectric	capacitance and dielectric loss																													
	dielectric response analysis (FDS, PDC)																													
chemical and oil analysis	DGA	X	X		O	X	X	X		O	X	X	O			O	O		X		O									X
	BV, color, IFT sediments, sludge, …																													
	moisture in oil																			X										
	conductivity, dielectric loss																													
	acidity																													
	particle analysis									O			O																	
	furan analysis																													
	corrosive sulphur analysis				X					X							X													
other	external inspection																			X			X							
	internal component inspection	O	X	X			O	X	X	X	X		X	X	X	O			O	O	X	O	X							X
	functional tests																								X	X		X	X	
	alarms																											O	O	
	fault recorder																													
	thermovision						O	O																						
	winding temperature																													
	core temperature																													
	CT tests																													
	vibration and acoustic analysis		O	O				O	X		X		X	X	X			X			O	O	X	X		O	O			

** If the defective over-voltage protection caused more arcing*

4.3.2 Dry Type Power Transformers

Due to the main insulation, dry-type power transformers differ significantly from oil-filled power transformers. The lack of transformer oil entails advantages, e.g. protected landscape, where a possible loss of oil must be prevented. Chemical and oil analysis is not applicable here. The solid epoxy-resin insulation has additional functions like providing mechanical strength and stability, but also different failure modes like cracks or treeing might develop. Therefore, appropriate diagnostic methods for the main insulation are not the same as for oil-filled power transformers. Furthermore, the heat transfer differs strongly, and the hot-spot behaviour differs.
Table 8 shows applicable methods for the active part, and Table 9 for tap changer and protection. It should be noted that dry-type transformers are rarely equipped with OLTCs. The table's methods can be applied to the seldom cases where an OLTC exists.

Table 8: Detection methods for the active part of dry-type transformers (X-suitable, O-possible, but less efficient)

	major component	winding / conductor											main					core						
	sub component	winding / conductor							Insulation		shielding elements		insulation					core steel/ laminates / sheets				insulation & connection to ground		core frame
	method / failure	turn-turn fault	coil-coil fault	coil-ground fault	lead-lead fault	lead-ground fault	short circuit between parallel strands	contact problem	insulation breakdown	localized hotspots	floating potential	short circuit	cracks	voids	delamination	surface contamination	localized hotspots	lamination insulation breakdown	moving sheets	core steel joint opening	corrosion of steel	insulation breakdown (double grounding)	core ground open	Insulation breakdown between core and frame or frame and frame parts
electric	turns ratio	X	O	X	X	X			X															
	insulation resistance			X	X				X							X						X*1		O*1
	winding resistance	X	O		X			X	X															
	exciting current	X										X						X		X		X		X
	short-circuit impedance	X	X				X																	
	induced voltage	X	X	X	X				X															
	applied voltage			X					X															
electric advanced	dynamic resistance	X						X	X															
	FRSL						X																	
	FRA	X	X	X	X	X		X	X		X							O		O			X	X
	PD analysis	X	X	X	X	X			X		X	X	x	x	X			X	O				X	O
dielectric	capacitance and dielectric loss			X	X				X		X					X						X*1	X*1	
	dielectric response analysis (FDS, PDC)			O	O				O		O					X						O*1	O*1	
other	external inspection									O			O	O		X	O				O			
	internal component inspection									O			O	O	O		O		X		X			
	functional tests																							
	alarms																							
	fault recorder		X	X	X	X			X															
	thermovision									x							X					X		
	winding temperature	X					X																	
	core temperature																							X
	CT tests																							
	vibration and acoustic analysis												O		O			X	X	X				

**1: If accessible via core ground bushing*

Table 9: Detection methods for tap changer (DETC, OLTC) and protection (X-suitable, O-possible, but less efficient)

	major component		deenergized tap changer (DETC)				on load tap changer (OLTC)*2																protection
	sub component		tap selector				tap and change-over selectors						diverter / selector switch						compartment		transition impedance		temperature relay
	method	failure	contact overheating	misalignment	corrosion	arcing	contact overheating	contact coking	misalignment	silver / copper corrosion	arcing, excessive sparking	partial discharge	excessive contact wear	loose or broken parts	excessive wear, backlash	overheating	silver / copper corrosion	bad transition time	leaks to mein tank	moisture ingress	broken resistors	reactor problems	loss of functionality
electric	turns ratio				O																	O	
	insulation resistance																						
	winding resistance		X		X		X	X		O			O			O	O					O	
	exciting current																					X	
	short-circuit impedance				O																	X	
	induced voltage				O	X						X											
	applied voltage				O	O						O											
electric advanced	dynamic resistance				X		X	X					O	O	O	O		X			X	X	
	FRSL				O																		
	FRA				O																		
	PD analysis					X						X											
dielectric	capacitance and dielectric loss																						
	dielectric response analysis (FDS, PDC)																						
other	external inspection																			X			
	internal component inspection		O	X	X		O	X	X	X	X		X	X	X	O			O	O	X	O	
	functional tests				O																		X
	alarms																						O
	fault recorder																						
	thermovision				O		O	O															O
	winding temperature																						
	core temperature																						
	CT tests																						
	vibration and acoustic analysis			O				O	X		X		X	X	X			X			O	O	

**2: An OLTC is rarely used for dry-type transformers*

4.3.3 Switchgear

Switchgears consist of numerous sub-components. Table 10 to Table 15 apply AIS and GIS and give an overview of inspection and diagnostic methods for each sub-component. The methods can be applied remotely (R) or locally (L), or both (R/L).

Table 10: Detection methods for main switching component and transmission of switchgear (R-remote, L-local)

				main switching component															trans-mission
	major component			sealing		main contacts			arcing contacts	arc quenching system		Vacuum interruptor	Mechanical chain		supporting pole			main circuits	
	sub component			o-ring	welding					medium	nozzle	bellow	contact springs						
	method	degradation / failure mode	_Remote (R) / Local Inspection (L)	leakage: ageing	leakage : corrosion	mechanical wear	electrical wear	welding		Leakage contamination	ablation carbonization	Punture nb of operations	relaxation	mechanical wear	dielectric surface degradation, PD, flashover	cracks	creep	screw torque loose corrosion	mechanical wear
electric	coil currents																		
	insulation resistance		L							L	L							L	
	main circuit resistance		L					L											
	continuous current																		
	dynamic resitance		L						L										
	auxiliary circuit resistance																		
	earthing circuit resistance																		
electric advanced	dynamic resistance																		
	DC Voltage test							L											
	manometer contact		R	R	R											R			
	integral arcing energy		R					R											
	motorization energy							?											
	PD analysis																	R/L	
mechanical	snatch gap (erosion gap)		L/R				L/R							L/R			L/R		
	time /space curves																		
	operating times																		
	speed sensors (motion test)					L/R		L/R					L/R	L/R					L/R
	vibration and acoustic analysis					L		L						L			L		L
	torque measurement																	L	
dielectric	capacitance & dielectric loss		L/R									L/R(vacuum)							
	dielectric withstand (DC, ..)							L		L	L				L				
chemical and medium analysis	DGA - gas analysis		L							L									
	moisture in medium (oil, gas)		L/R							L/R									
	conductivity, dielectric loss		L							L (oil)									
	sniffer		L/ R	L	L											L			
pressure monitoring	density		L/R	L/R	L/R														
	manometer (visual)		L	L	L														
other	external/visual inspection				L														
	mechanichal operation count		R/L					R/L				R/L							
	functional tests														L				
	alarms / event recorder																		
	fault recorder		R					R											
	thermovision																	L	
	CT tests (Ratio)																		

Table 11: Detection methods for operating mechanism and disconnectors of switchgear (R-remote, L-local)

			operating mechanism													disconnectors				
	major component		Mechanical components								electrical components			auxiliary circuit	tripping coil	line disconnector		withdrawable breaker		
	sub component		main spring	power		interlocks	operation counter	position-indicating/signalling device	position-signalling kinematic chain	lever	motor	motor electrical control	wires	auxiliary contact		contact (welding,	shaft	contact	interlocks	racking system
	method	degradation / failure mode _Remote (R) / Local Inspection (L)	Breaking corrosion / relaxation	Break	mechanical wear grease ageing	Break	Break	Break	Break	Break	mechanical wear	overheating	deconnexion	welding	overheating	mechanical wear	mechanical wear	mechanical wearing	break	mechanical wear
electric	coil currents												L		L					
	insulation resistance	L																		
	main circuit resistance	L														L		L		
	continuous current																			
	dynamic resitance	L																		
	auxiliary circuit resistance												L	L						
	earthing circuit resistance																			
electric advanced	dynamic resistance																			
	DC Voltage test															L				
	manometer contact	R																		
	integral arcing energy	R																		
	motorization energy			L							R/L	R/L								
	PD analysis																			
mechanical	snatch gap (erosion gap)	L/R		L/R	L/R															
	time /space curves				L/R															
	operating times				L/R															
	speed sensors (motion test)			L/R	L/R															
	vibration and acoustic analysis		L	L							L									
	torque measurement																			
dielectric	capacitance & dielectric loss	L/R																		
	dielectric withstand (DC, ..)															L				
chemical and medium analysis	DGA - gas analysis	L																		
	moisture in medium (oil, gas)	L/R																		
	conductivity, dielectric loss	L																		
	sniffer	L/ R																		
pressure monitoring	density	L/R																		
	manometer (visual)	L																		
other	external/visual inspection															L	L	L		L
	mechanichal operation count	R/L					L	L	L	L						R/L		R/L		
	functional tests					L		L	L		L	L	L	L	L		L	L	L	L
	alarms / event recorder										R/L	R/L								
	fault recorder	R									R/L	R/L								
	thermovision															L				
	CT tests (Ratio)																			

Table 12: Detection methods for grounding (earthing switch), insulation medium and busbar of switchgear (R-remote, L-local)

			grounding (earthing) switch			insulation medium				busbar		
	major component					GIS			AIS	contact	insulation	
	sub component		contact	interlocks	mech	gas pressure	humidity	by-products	humidity	contact		
	method degradation / failure mode	_Remote (R) / Local Inspection (L)	welding	break	mechanical wear	leakage	corrosion for metal corrona /tracking for insulators		corrosion for metal corrona /tracking for insulators	loose connection, oxydation, overheating	surface degradation, PD, flashover, Mech	surface degradation, PD, flashover
electric	coil currents											
	insulation resistance	L									L	
	main circuit resistance	L								L		
	continuous current											
	dynamic resitance	L										
	auxiliary circuit resistance											
	earthing circuit resistance		L									
electric advanced	dynamic resistance											
	DC Voltage test											
	manometer contact	R				R						R/L
	integral arcing energy	R										
	motorization energy				R/L							
	PD analysis											
mechanical	snatch gap (erosion gap)	L/R										
	time /space curves											
	operating times											
	speed sensors (motion test)											
	vibration and acoustic analysis											
	torque measurement									L		
dielectric	capacitance & dielectric loss	L/R										
	dielectric withstand (DC, ..)					L					L	L
chemical and medium analysis	DGA - gas analysis	L						L				
	moisture in medium (oil, gas)	L/R					R/L					
	conductivity, dielectric loss	L										
	sniffer	L/ R				L						
pressure monitoring	density	L/R				R						R
	manometer (visual)	L				L						L
other	external/visual inspection											
	mechanichal operation count	R/L	R/L									
	functional tests			L	L							
	alarms / event recorder					R/L						
	fault recorder	R										
	thermovision									L		
	CT tests (Ratio)											

Table 13: Detection methods for main circuit, cable and bushings of switchgear (R-remote, L-local)

			main circuit		cable		bushing	
	major component		contact	insulation	contact	insulation	contact	insulation
	sub component							
	method / degradation / failure mode	_Remote (R) / Local Inspection (L)	loose connection, oxydation, overheating	surface degradation, PD, flashover	loose connection, oxydation, overheating	surface degradation, PD, flashover	loose connection, oxydation, overheating	surface degradation, PD, flashover, Mech.
electric	coil currents							
	insulation resistance	L						
	main circuit resistance	L	L		L		L	
	continuous current							
	dynamic resitance	L						
	auxiliary circuit resistance							
	earthing circuit resistance							
electric advanced	dynamic resistance							
	DC Voltage test			L		L		L
	manometer contact	R						
	integral arcing energy	R						
	motorization energy							
	PD analysis			R/L		R/L		R/L
mechanical	snatch gap (erosion gap)	L/R						
	time /space curves							
	operating times							
	speed sensors (motion test)							
	vibration and acoustic analysis							
	torque measurement							
dielectric	capacitance & dielectric loss	L/R		L		L		L
	dielectric withstand (DC, ..)			L		L		L
chemical and medium analysis	DGA - gas analysis	L						
	moisture in medium (oil, gas)	L/R						
	conductivity, dielectric loss	L						
	sniffer	L/ R						
pressure monitoring	density	L/R						
	manometer (visual)	L						
other	external/visual inspection							
	mechanichal operation count	R/L						
	functional tests							
	alarms / event recorder							
	fault recorder	R						
	thermovision		L		L		L	
	CT tests (Ratio)							

Table 14: Detection methods for instrument transformers of switchgear (R-remote, L-local)

				instrument transformers																		
	major component			low power current transformer				inductive current transformer			low power voltage transformer				inductive voltage transformer				capacitive voltage transformer			
	sub component			winding	insulation	elctronics	contacts	winding	insulation	contacts	winding	insulation	elctronics	contacts	winding	insulation	contacts	fuse	insulation	capacitors	racking system	contacts
	method	degradation / failure mode	_Remote (R) / Local Inspection (L)	overvoltage, short - circuited turns	surface degradation, PD, flashover	overvoltage, overheating	loose connection, oxydation, overheating	overvoltage, short - circuited turns	surface degradation, PD, flashover	loose connection, oxydation, overheating	overvoltage, short - circuited turns	surface degradation, PD, flashover	overvoltage, overheating	loose connection, oxydation, overheating	overvoltage, short - circuited turns	surface degradation, PD, flashover	loose connection, oxydation, overheating	LV short -circuit	surface degradation, PD, flashover	overvoltage	break	loose connection, oxydation, overheating
electric	coil currents																					
	insulation resistance		L																			
	main circuit resistance		L							L												
	continuous current																					
	dynamic resitance		L																			
	auxiliary circuit resistance																					
	earthing circuit resistance																					
electric advanced	dynamic resistance																					
	DC Voltage test				?				L			?				L						
	manometer contact		R																			
	integral arcing energy		R																			
	motorization energy																					
	PD analysis								R/L							R/L			R/L			
mechanical	snatch gap (erosion gap)		L/R																			
	time /space curves																					
	operating times																					
	speed sensors (motion test)																					
	vibration and acoustic analysis																					
	torque measurement																					
dielectric	capacitance & dielectric loss		L/R																	L		
	dielectric withstand (DC, ..)																					
chemical and medium analysis	DGA - gas analysis		L																			
	moisture in medium (oil, gas)		L/R																			
	conductivity, dielectric loss		L																			
	sniffer		L/ R																			
pressure monitoring	density		L/R																			
	manometer (visual)		L																			
other	external/visual inspection				L		L		L	L		L		L		L	L	L	L			L
	mechanichal operation count		R/L																			
	functional tests					L							L									
	alarms / event recorder																					
	fault recorder		R																			
	thermovision			L			L															
	CT tests (Ratio)			L							L									L		

Table 15: Detection methods for other transformers, fuse holders, shutter and insulator of switchgear (R-remote, L-local)

			other transfor-mers		fuse holder			shutter (withdraw able CB)			insu-lator
	major component		transformer for auxiliary power supply		holder	fuse		shutter	mechanics	interlock	
	sub component		insulation	contacts	insulation	contact	tripping link				
	method degradation / failure mode	Remote (R) / Local Inspection (L)	surface degradation, PD, flashover	loose connection, oxydation, overheating	surface degradation, PD, flashover	loose connection,	break	break	mechanical wear	vbreak	surface degradation, PD, flashover
electric	coil currents										
	insulation resistance	L									
	main circuit resistance	L									
	continuous current										
	dynamic resitance	L									
	auxiliary circuit resistance										
	earthing circuit resistance										
electric advanced	dynamic resistance										
	DC Voltage test										
	manometer contact	R									
	integral arcing energy	R									
	motorization energy										
	PD analysis										R/L
mechanical	snatch gap (erosion gap)	L/R									
	time /space curves										
	operating times										
	speed sensors (motion test)										
	vibration and acoustic analysis										
	torque measurement										
dielectric	capacitance & dielectric loss	L/R									
	dielectric withstand (DC, ..)				L						L
chemical and medium analysis	DGA - gas analysis	L									
	moisture in medium (oil, gas)	L/R									
	conductivity, dielectric loss	L									
	sniffer	L/ R									
pressure monitoring	density	L/R									
	manometer (visual)	L									
other	external/visual inspection				L	L	L	L			L
	mechanichal operation count	R/L							R/L	R/L	
	functional tests						L	L	L	L	
	alarms / event recorder						R/L				
	fault recorder	R					R/L				
	thermovision					L					
	CT tests (Ratio)										

Table 16: Detection methods for other surge protection, enclosure and control panel of switchgear (R-remote, L-local)

			surge protec- tion	enclosure						control panel				
	major component			enclosure	tank		door	partition	pressure relief	terminal	auxilary circuit	protection relay	VPIS, VDS, VDIS	manometer
	sub component		active part											
	method degradation / failure mode	_Remote (R) / Local Inspection (L)	over-current over-heating	corrosion	corrosion	Leakage	corrosion	corrosion	leakage	loose connection , serial arc	over heating, non-operation	over voltage, over heating, non-operation	over volatage, non-indication	leakage, false-indication
electric	coil currents													
	insulation resistance	L	L											
	main circuit resistance	L												
	continuous current													
	dynamic resitance	L												
	auxiliary circuit resistance										L			
	earthing circuit resistance													
electric advanced	dynamic resistance													
	DC Voltage test													
	manometer contact	R												
	integral arcing energy	R												
	motorization energy													
	PD analysis													
mechanical	snatch gap (erosion gap)	L/R												
	time /space curves													
	operating times													
	speed sensors (motion test)													
	vibration and acoustic analysis													
	torque measurement													
dielectric	capacitance & dielectric loss	L/R												
	dielectric withstand (DC, ..)													
chemical and medium analysis	DGA - gas analysis	L												
	moisture in medium (oil, gas)	L/R												
	conductivity, dielectric loss	L												
	sniffer	L/ R												
pressure monitoring	density	L/R												
	manometer (visual)	L												
other	external/visual inspection		L	L	L		L	L	L	L				L
	mechanichal operation count	R/L												
	functional tests										L	R/L	L	L
	alarms / event recorder		R/L				R/L		R/L		R/L	R/L	R/L	
	fault recorder	R	R/L											
	thermovision													
	CT tests (Ratio)													

4.3.4 Cables

Distribution cables are composed of several product sub-families based on their usage, installation mode and the voltage level of the network. As major product segmentation, one can distinguish insulated versus bare conductors cables, underground versus aerial cables and low voltage versus medium voltage cables. While not applicable to all sub-families, cables have four main sub-components: the conductor, the insulation system, the screen and the protective sheath. Considering cables' relatively high operating lifetime, several technologies co-exist in distribution networks for each subcomponent, leading to a wide range of design combinations.

Table 15 Main diagnosis and health assessment techniques and methods applicable for synthetic-insulated cables of both medium and low voltage (X-suitable, O-possible, but less efficient)

			Insulated cable																
	major component		Insulation					Screen					Sheath						
	method	failure	Water treeing	electrical breakdown	partial discharge	mechanical destruction	thermal oxidation	moisture intrusion	oxidative corrosion	grounding continuity disruption	galvanic corrosion	short circuit overshoot	mechanical integrity destruction	Thermal oxidation	Chemical aggression	Photo-oxidation	Overbending stress cracking	Water ingress	Impact
Electric test	Voltage test		X	X	X														
	sheath test									O			X	O	O	O	X		
	Tan delta		X	X			X												
	Partial discharge			O	X	O	O												
	Time Domain Refectometry			X		X				X									
	Breakdown voltage test		X	X			O	O											
	Continuity									X									
Chemical analyses	Moisture content (KFT)		X					X										X	
	Thermal testing (DSC)						X						°	X	X			O	
	Chemical composition (TGA)						O							O					
	Oxidative product analysis (FTIR)						X		O							X			
	Tensile measurements		O				X							X	X	X			
	Thermomechanical strength (HST)						X							X	X	X			
Other	Optical microscopy observation		X	X					X		X								
	Visual inspection			X		X			X		X	O	X				X	X	X
	Accelerated ageing			X			X							X		X			

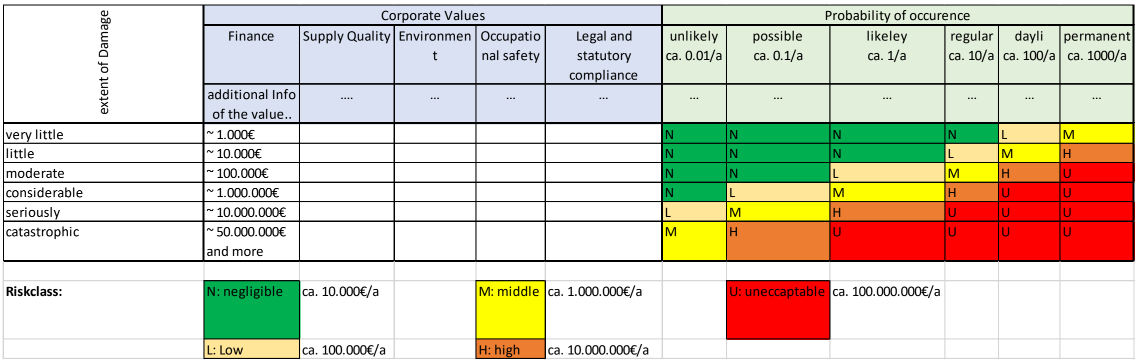
5 Case Studies for Lifetime Extension Strategies

5.1 Lessons Learned from Distribution System Operators

This example covers the experience of Stromnetz Hamburg GmbH (SNH) regarding time- or condition-based maintenance and dealing with risk-based approaches according to ISO 55000. Initially, maintenance work was time oriented at SNH. It means every equipment or system has a fixed temporal cycle for inspections and maintenance. Over time the strategy evolved, and regarding the pros and cons, SNH switched strategy to condition-based maintenance for all equipment. The aim was less OPEX and a cost-optimized approach for maintenance. After a short while, SNH noticed the cons of such a strategy. Work was not plannable on the technical side and the human resource management. It was harder to plan work and get a better asset base. The risk of failure constantly increases because of missing inspections and maintenance. There is also lacking information about your asset's conditions. Evaluating both strategies led to the time-based orientated approach, again combining this with the basic idea of ISO 55000. Strategic planning nowadays focuses on risk-based asset management plus having fixed cycles for inspections and maintenance to understand all electrical equipment better and, of course, know the condition.

Risk-based asset management covers the monetarization and probability of certain events that could negatively impact the stakeholders. It means that every event becomes a number representing the risk's value. The following table clarifies that. Regarding the risk matrix, maintenance costs and amounts will be assigned from the asset management to the asset service to minimize the overall company risks.

A good example is the oil sump basins at the network stations. There are a few stations which still have not installed any oil leaking precautions. This risk can be directly transferred to the risk matrix and corporate values such as Environment, legal compliance and occupational safety. Hence it can be monetized and gets a high priority in the future planning of maintenance at network stations. Network stations without any oil sump basins should be fixed first. The important thing in using a risk-based strategy is knowing the risks regarding every piece of electrical equipment, prioritising them and making plans to solve them as well as possible.



extent of Damage	Corporate Values					Probability of occurence					
	Finance	Supply Quality	Environment	Occupational safety	Legal and statutory compliance	unlikely ca. 0.01/a	possible ca. 0.1/a	likeley ca. 1/a	regular ca. 10/a	dayli ca. 100/a	permanent ca. 1000/a
	additional Info of the value..	....	...	...	...	...	...	...	...	...	...
very little	~ 1.000€					N	N	N	N	L	M
little	~ 10.000€					N	N	N	L	M	H
moderate	~ 100.000€					N	N	L	M	H	U
considerable	~ 1.000.000€					N	L	M	H	U	U
seriously	~ 10.000.000€					L	M	H	U	U	U
catastrophic	~ 50.000.000€ and more					M	H	U	U	U	U
Riskclass:	N: negligible	ca. 10.000€/a		M: middle	ca. 1.000.000€/a		U: uneccaptable	ca. 100.000.000€/a			
	L: Low	ca. 100.000€/a		H: high	ca. 10.000.000€/a						

Table 17: Example of a risk-matrix

Vattenfall Eldistribution, hereafter Vattenfall (together with many other DSOs of today), aims towards a predictive maintenance approach. Maintenance is scheduled based on assessed asset condition and estimated degradation time to ensure performance and functionality. The method requires precise condition assessment and/or reliable data models predicting when maintenance measures should be taken to keep the asset health within a condition that provides functionality and reliability.

A prerequisite for Vattenfall towards predictive and risk-based maintenance (and following ISO 55 000) was the need for health indices applicable to the asset population. However, health indices should be built on asset data. It was identified early that one of the main challenges within this area is associated with the availability of information and data since information not uncommonly is unavailable, limited or stored in a non-structured way.

In 2019 Vattenfall chose an exploratory approach enabling data evaluation and decision-making based on already available information gathered from currently existing data sources, merged to aggregate all information to corresponding assets. This methodology resulted in a tool that allowed the development of health indices with a bottom-up approach. Since health indices are given to every individual asset, aggregations and comparisons can also be made on an asset group level, geographical areas between asset groups with more.

The methodology is based on threshold values for health-impacting events/measurements, with the setback that to get results compliant to both trends and already investigated influences, the method requires a time-consuming calibration at the same time as the threshold values must be constantly monitored and questioned to keep health indices up to date. Also, some data “cleaning” might be required since external factors such as unconventional weather, for instance, might greatly impact results.

Last, this is Vattenfall’s approach towards predictive and risk-based maintenance. For the risk evaluation, Vattenfall developed a risk matrix in line with Stromnetz Hamburg describing corporate values and an estimated probability. In this context, the health indices should be important for describing and evaluating the probability of events resulting in described corporate risks, which is not fully achieved today.

Evaluating the outcome of Vattenfall’s exploratory approach gives great potential for further development of health indices, especially with a closer alignment with probability in the risk matrix. Assembling data into health indices also helps acknowledge deviations in asset performance in large asset populations, identifying which assets need further attention. However, since continuous inspection data is a prerequisite for evaluating asset degradation for this method, elements of time-based maintenance will also be needed in a predictive and risk-based maintenance approach. Hence, maintenance optimisation should include risk assessment originating from event scenarios and how efficiency can be improved by planning and already planned actions.

5.2 Asset Management of a DSO with Example for Cables

Vorarlberger Energienetze GmbH (vorarlberg netz for short) is a subsidiary of illwerke vkw AG and is responsible for operating the electricity and natural gas networks. [39]
The asset management (asset management system) at vorarlberg netz is based on the structure and terminology used on the international standard ISO 55000. This ISO 55000 alignment was particularly important in the strategic asset management plan and the asset management plans. The strategic asset management plan is the central document for asset management at vorarlberg netz. The principles and framework of the AM management system are based on the corporate principles and goals, the legal and regulatory environment and the requirements to be met within the scope of the certifications.

a) Goals and tasks

An essential asset management task at vorarlberg netz is to plan target values for availability, operating and maintenance costs, and investments in the medium and long term. These are then coordinated with the management by those responsible within the budget framework. The goals are formulated annually and, if necessary, adjusted to the given framework conditions.
Asset management is a systematic, continuous optimization of the renewal and maintenance strategy and its concepts and plans concerning high network availability and optimal use of funds.
The main tasks are:

- Provide methods for the systematic, ongoing optimization of the renewal and maintenance strategy
- Methodically support the employees of the responsible departments in optimizing the renewal and maintenance strategy
- Provide control information for the management (expected development of future financial needs for the maintenance, renewal and troubleshooting of network systems)
- Create the necessary framework and requirements for the gradual improvement of the available database
- Formulate requirements for the IT systems from the point of view of "optimization maintenance strategy".
- The initiated optimization cycle of the renewal and maintenance strategy will be maintained by asset management in the future
- To develop the renewal and maintenance strategy, voltage quality in the medium and low voltage network and strategic network planning and reliability are also considered.
- For the development of the renewal and maintenance strategy, the aspects of (n-1) safety in the high and extra-high voltage network, strategic network planning, and reliability are considered.
- Development, ongoing adjustment and coordination of the renewal and maintenance strategy for the networks by minimizing the technical, financial and safety-related risks (of network operation) with the aim of sustainable, optimized use of budget funds (economic, regulatory and strategic) for network investments and maintenance.

The essential tasks related to asset management lead to roles set up in an organization as internal or external functional units. [40]

At vorarlberg netz, renewal and maintenance measures are carried out by the service provider (responsible departments) in coordination with the asset owner and asset manager (management and responsible organizational units) following the specifications in the strategic asset management plan. Manufacturers and external companies are consulted in special cases, such as special revisions or TÜV (Technischer Überwachungsverein, German for Technical Supervisory Association) tests on certain devices or systems.

The tried and tested pragmatic approach to lifetime extension options for electrical equipment at Vorarlberg netz includes the following:

- cost/benefit of sensors, diagnostic and monitoring tools must be in a good relationship
- economically sensible solutions (focus on network tariffs, supply reliability)
- not always taking the „ideal“ route of the most extensive monitoring available on the market with the associated flood of data
- target and problem-oriented diagnoses (e.g. for transformers, stations, type-specific problems on switchgear, cable technologies etc.)
- age structure and its forecast of selected electrical equipment (asset simulation)
- asset management system, based on principles of ISO 55000

b) Description of appropriate maintenance and replacement strategy using the example of cables

At vorarlberg netz, high- and medium-voltage cables should have the longest possible service life cycles. For these cables to have a service life of at least 40 years and more, a solid starting product and appropriate maintenance are required. The maintenance measures are also individually adapted to the respective type.

Inspection

Various checks and tests (visual checks, electrical measurements/tests and chemical/physical tests) are carried out periodically to determine whether the high- and medium-voltage cables are in an operationally safe condition. It should also be possible to derive measures to prevent faults and increase operational safety from these findings if necessary.

Since the service life of the high and medium voltage cables, including their fittings, can be assumed to be at least 40 years under normal power supply and load conditions, a random assessment of the condition should be done for the first time after this period has expired. After that, the condition assessment must be repeated every 10 years. In the case of medium-voltage cables, the voltage test is primarily used for this assessment because the diagnostic methods available on the market sometimes lead to incorrect diagnoses.

In the case of high-voltage cables, measurements and tests to assess the current condition of the insulation should be carried out by external service providers on a case-by-case basis.

The maintenance activities include

- visual control
- functional check and mechanical investigations
- oil investigation
- electrical measurements and tests
- Test and control intervals

Table 18: Activities for high and low-pressure oil cable systems concerning visual inspection, functional and mechanical checks

Activity	High and low pressure oil cable system	lead-cased cable system	Mixed cable system	PVC cable system	Line route	Substation supervisor operations center	specialist staff	extern
Visual control								
Check oil level		X	X			yearly		
Check oil pressure	X					yearly		
Oil system leaks	X						yearly	
Line route control					X		if necessary	
Function check and mechanical check								
Pressure monitoring	X						yearly	
Lead embrittlement	X							if necessary
Thermographic analysis line end.				X			if necessary	

Table 19: Activities for high and low-pressure oil cable systems concerning oil analysis, electrical measurements and tests

Activity	High and low pressure oil cable system	lead-cased cable system	Mixed cable system	PVC cable system	Line route	Substation supervisor operations center	specialist staff	extern
Oil analysis								
Breakdown voltage	X							if necessary
Moisture content	X							if necessary
Dielectric dissipation factor	X							if necessary
TCG Sum all gases	X							if necessary
Electrical measurements and tests								
cable sheath insp.				X		5 years	5 years*	
AC voltage test			X	X			10 years	if necessary
DC voltage test	X	X					10 years	if necessary
Partial discharge measurement	X	X	X	X				if necessary
tan δ – measurem.	X	X	X	X			if necessary	if necessary
Insulation measur.				X			if necessary	

Replacement strategy

The end of the technical service life of high and medium-voltage cables is generally assumed to be when they reach 40 years. After this limit has been reached, a periodic voltage test or diagnostic measurement should be used to prove that the cables still have sufficient operational reliability and can remain in operation for 10 years.

High voltage cable

In the case of high-voltage cables, the actual condition of the insulation should be assessed by external service providers for the first time after 40 years of operation. The test, measurement and diagnostic methods available on the market are used. The stress level for the diagnostic procedures is based on the proposal of the CIGRE working group and is summarized in Table 18 and Table 19.

If the high-voltage cable is attested to have sufficient operational safety in this assessment, the assessment is only repeated after a further 10 years of operation. If the measurement and diagnostic procedures indicate operationally aged insulation with an increased probability of failure, the replacement priority for this high-voltage cable is determined.

Table 20: Voltage stress for diagnostic procedures on service-aged high-voltage cables with VPE insulation

U_N	cable age ≤ 5 years		cable age > 5 years	
	U_p	measurement duration	U_p	measurement duration
[kV]	[kV]	[h]	[kV]	[h]
66	72 (2,0*U_0)	1	58 (1,6*U_0)	1
110	128 (2,0*U_0)	1	103 (1,6*U_0)	1
220	180 (1,4*U_0)	1	152 (1,2*U_0)	1

Medium voltage cable

In the case of medium-voltage cables, the actual condition of the insulation should be determined by the company's specialists for the first time after 40 years of operation. Mixed and plastic cable sections are tested using a 0.1 Hz AC voltage test with 3* U_0. A DC voltage test with a test voltage of 5* U_0 is used for lead-sheathed cables.

The medium-voltage cables are selected randomly, with each category comprising around 20% of the test items (the annual focus here is particularly on cable sections or sections with an operating age of 40 and 50 years). The following measures are derived from this:

voltage test		
passed	failed	With a failure rate > 25% failed/checked
Cable operational for another 10 years	Repair cable and set replacement priority 1 to 3	The further procedure and the necessary measures are mutually agreed upon in coordination with the specialist departments.

Replacement priority

Operationally aged high and medium-voltage cables are divided into three categories, each assigned a specific replacement priority.

Replacement priority 1: Due to the condition of the HS and MV cables, these must be replaced immediately.

Replacement priority 2: Cables with this priority should be replaced in the medium term. A ranking within this category takes place in coordination with the specialist departments, depending on the importance of the installation location (importance).

Replacement priority 3: Due to their condition, cables in this category can continue to be operated, with the future interval of the condition assessment being reduced to five years.

5.3 Condition Assessment of a Transformer Fleet with 2D-Approach

This case study presents an approach for a fleet assessment of power transformers. Since the 2-dimensional approach was first published in 2017, various optimizations have been developed and implemented to support the electrical equipment and service managers [35]. One example is data uncertainty. This fact always appears in reality, and the question is how conscious the responsible asset manager is about the fact that the data quality is not optimal. What consequences does it have on the decisions, and which possibilities are available to decrease the data uncertainty if necessary? Data uncertainty has many causes - ranging from the measurement method's accuracy to the parameters' suitability to the age of the diagnostic data, among others. There is growing awareness that asset managers are also responsible for correctly defining the strategies to handle the data quality (ex: ISO 55000), which means implementing the necessary measures to evaluate the uncertainty.

c) Data Acquisition

The information situation in the field differs from case to case significantly. If the condition of a transformer is to be determined on-site, the service technician will find different conditions practically every time. One of the most challenging topics for responsible service managers is the time planning for costly outages of transformers to make necessary measurements. In addition, training, scheduling of the internal staff, and consideration of already available (historical) data make the existing task even more difficult.

A major issue for utilities is the availability of data on old power transformers, which might be very poor. The data is usually homogeneous in format or storage form (paper, digital, etc.) [21]. For this reason, a pragmatic “three-level approach” has been developed to address the mentioned topics. Moreover, using this approach, the necessary level of data quality can be achieved most efficiently (Table 21).

Table 21 Structuring of the input parameters into information packages, considering data quality

	Input data	**Data quality (DQ) and Purpose (P)**
1st Level Assessment (No outage required)	**Existing data** (main transformer data, maintenance history, all available historical measurements data (Visual inspection, oil analysis, DGA, electrical measurements, IR-thermography)	DQ: differs significantly depending on the situation (completeness and age of the data). P: In most cases appropriate for initial fleet ranking and clustering for the next steps
2nd Level Assessment (No outage required)	**Data from the field during the transformer operation** (Non-disruptive tests: Visual inspection, oil analysis, DGA, Furan and Methanol analysis, IR-thermography)	DQ: very reliable data basis for further decisions P: Detailed fleet condition assessment of targeted clusters for further steps like prioritization of maintenance & lifetime extension measures, CAPEX & OPEX budget planning
3rd Level Assessment (Outage required)	**Data from disruptive tests (e.g. electrical measurements** (Winding resistance, Magnetization current, Short circuit impedance, SFRA Transformer, Turn Ratio, PDC/FDS measurement, Power factor/tan δ etc.)	DQ: optimal data basis P: Confirmation or refutation of the suspicious results from Levels 1 and 2 (e.g. assumption for a failure)

The data are normally available from the system operator and represent the initial package (1st Level Assessment). With this information, the groups of transformers from the fleet that should be subjected to a closer on-site investigation can be preselected. The data quality differs significantly from case to case. Some utilities regularly conduct very detailed analyses and consequently achieve low data uncertainty. Data uncertainty is often high because of a lack of information or outdated data. In these cases, further steps are recommended.

The 2nd Level Assessment is the standard, basic on-site appraisal of a transformer during operation. At this stage, a condition assessment is carried out based on the visual inspection (inspection checklist) and non-disruptive tests such as the oil condition tests, DGA and thermography. The 3rd Level Assessment includes all additional test methods that can be used on transformers in the field to achieve a comprehensive condition assessment. For this purpose, however, it is necessary to take the transformer offline. This 3rd Level of Assessment should be limited to targeted situations where the results established based on the previous information packages have identified a suspicious unit or when a unit is preselected for a major reinvestment. Experience [8, 9, 10] shows that this level is typically required only for a small percentage of any transformer fleet.

d) *Analysis and Visualization*

The following example shows data uncertainty's impact on the asset managers' decisions in a practical case. The transformer under consideration is 21 years old and is operated by a German utility.

Initially, data acquisition within the Level 1 scope was performed, and the 2-dimensional approach was applied for the detailed condition assessment.

Level 1 assessment is, as shown in Table 1 above, an analysis of already existing data. The utility provided four years old oil and DGA results. The values were within the given limits and did not show any abnormalities. The DP value is evaluated based on the furan analysis. In addition, some visual inspection points could also be evaluated. Further measurements like thermography or electrical measurements were not available.

The analysis using the algorithm [35] and the data uncertainty model is shown below (Figure 11). The transformer is evaluated as normal operation (black dot). Still, due to a large amount of missing data and the age of the data, there is a very high data uncertainty, whose range is indicated by the dotted square.

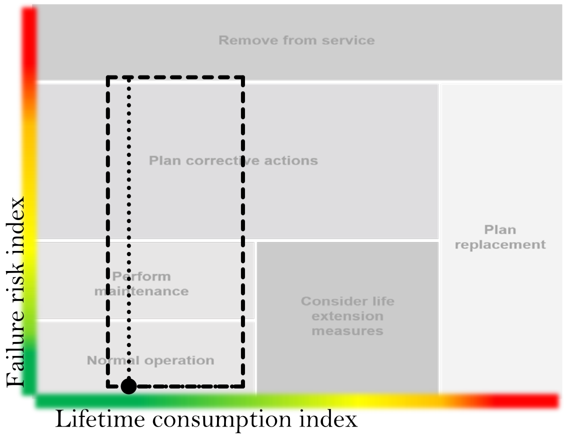


Figure 11 Level 1 Assessment

Due to this very uncertain condition assessment, which includes the area of "planning repair measures", the transformer expert recommended conducting Level 2.

During the Level 2 condition assessment, the missing assessment points of the visual inspection (VI), the values from the thermography, updated oil analysis including DGA as well as furan analysis are obtained. During the VI, leaks on the transformer tank and bushings could be detected. In addition, the used silica gel (silica gel is discoloured and 50% missing) in the dehydrating breather could be identified. The current oil analysis reveals that the oil moisture had increased (40 ppm), and the breakdown voltage had reduced (55 kV). The detailed methanol and furan analysis showed a deteriorated DP value of 500 (previously 650). The updated measurements and assessments resulted in the following condition rating Figure 12.

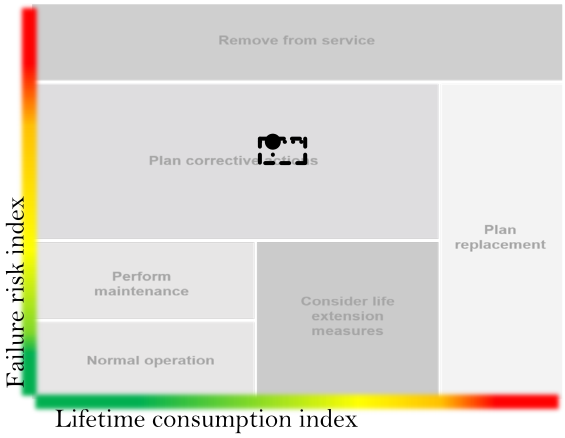


Figure 12 Level 2 Assessment

e) *Derivation of Recommendations*

The transformer is now precisely placed (low uncertainty range shown by the dotted square) in the "Plan repair measures" area. The data uncertainty is significantly reduced, enabling the responsible asset manager to make the proper decision with high confidence on the appropriate next steps towards ensuring a reliable and sustainable transformer operation. Due to the high moisture in the oil and the low breakdown voltage, the utility was recommended to perform a PDC/FDS measurement to more precisely determine the moisture in the oil, especially in the paper insulation. In addition, it is recommended to take another oil sample to analyze the DGA trend, and this determination serves to reduce the data uncertainty further.

The utility followed the recommendations and conducted the Level 3 assessment, including the PDC/FDS measurements and additional oil analysis. Subsequently, the paper and oil moisture proved to be excessively high. In addition, the data uncertainty could be reduced by 25,4 % due to the performance of another measurement and consideration of the DGA trend.

In summary, the following recommendations have been made by the transformer experts:

- Repair leakages (transformer tank and bushings)
- Refill silica gel in the dehydrating breather
- Perform a long-term online drying process of the oil and paper isolation

The recommendations have been implemented, thus reducing the moisture in oil to a low level (4 ppm). The paper moisture decreased from 3,4 % to 1,7 % due to long-term oil drying. Also, the breakdown voltage could be improved (75 kV).

Figure 13 shows the condition of the transformer after all recommendations were implemented. The asset manager could move to a safe condition in the “normal operation” area. A certain residual uncertainty remains due to the theoretically incomplete data input into the algorithm (e.g. further electrical tests). It must also be remembered that, due to the logarithmic visualization of the 2D-Matrix, the geometric area of the uncertainty plotted in the field “normal operation” is wider than in the fields located around. This transformer does not have a high criticality (strategic importance), does not show a high failure risk, and simultaneously, the lifetime consumption is not advanced; it is reasonable to forego any additional measurements.

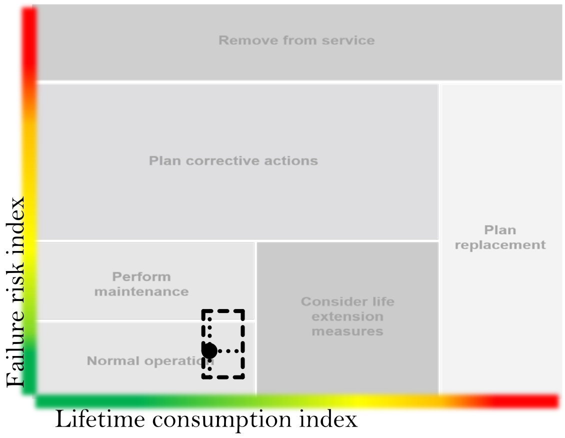


Figure 13 Assessment after repair

f) Discussion of Consequences for Asset Management

This practical example highlights the importance of the data in the condition assessment process. Depending on the situation (data availability, criticality, condition of the electrical equipment, AM strategy and risk affinity etc.), different levels of data uncertainty can be acceptable. Some abnormalities could be identified and eliminated in the discussed case after a three-level approach. The data quality could be dramatically improved with every step during this approach. Because of the low risk of failure and no advanced lifetime consumption, a remaining but very low level of data uncertainty could be accepted.

5.4 Fault diagnostics of power transformers using machine learning

This chapter presents some initial results from fault diagnosis of power transformers using novel methods with machine learning. The case study of a power transformer develops a data-driven fault diagnosis utilizing deep learning for high-voltage equipment condition monitoring. The resulting approach provides a predictive approach for maintenance, a method for preventive maintenance, and input to Stage 2 in an RCAM study according to chapter b) on systematic approaches for AM.

This case study develops a data-driven fault diagnosis utilizing operation data for high-voltage equipment condition monitoring. An interview with an expert was conducted to understand the asset management of power transformers. The proposed approach uses deep learning in an unsupervised way to model normal behaviours and identify underlying operational risks. The autoencoders are used to compress the raw data and extract the key features and the recurrent gated unit to model the dependencies between normal behaviours of power transformers. Finally, the method employs control charts to generate the alarm to indicate the underlying anomalies. The study uses an online dataset to test the applications for sensor failures. The results show that the method can identify operational risks before sensor failures. The complete case study is presented in [41].

a) Introduction

As discussed previously in the report, asset management is a coordinated activity for the organization to get value from electrical equipment. As the main part of asset management, maintenance includes all the technical and corresponding administrative actions to keep or restore the electrical equipment to the desired state in which it can perform its required functions [2]. Traditional maintenance is usually based on scheduled monitoring and physical inspections. With the industrial Internet of Things developing, more and more operation data could be accessible and condition-based maintenance shows promise for electrical equipment. A power transformer introduces mutual coupling by electromagnetic induction to transfer electric energy between the generator and the distribution network [42]. The power transformer typically contains the core, winding, tap changers, bushing, cooling, and other auxiliary systems [43]. As the most crucial equipment in the transmission networks, the power transformer affects the operation reliability of power networks. The Cigré survey collected 964 major failures between 1996 and 2010 from 21 countries [38], which require the transformer to be removed from service longer than seven days. The failure modes are classified into six categories: dielectric, electric, thermal, physical chemistry, mechanical and unknown. More details can be found in Table I. The survey found that dielectric failures were the top contributors, up 36.62% of the total failure events. Winding, tap changer, and bushing are the top three components with the most major failures reported. In [44], the ageing effect of temperature, moisture, and oxygen was discussed and tested using online monitoring methods. Reference [45] analyses and summarizes the brushing component's failure mechanism and rate. The survey [38] also revealed that design, ageing, and external short circuits are the three major causes. It is also noted that 29% of failures were due to unknown causes, which shows that it is difficult to identify the root cause of a failure event.

Table 22 Failure modes of power transformers [41]

Types	Failures
Dielectric	Partial discharge, tracking, flashover
Electrical	Open Circuit, Short Circuit Poor Joint, Poor Contract
Thermal	General overheating, localized hotspot
Physical Chemistry	Contamination (moisture, particle, gas), corrosion
Mechanical	Bending, breaking, displacement, loosening, vibration
Unknown	-

The classical health assessment includes dissolved gas analysis (DGA), partial discharges analysis, moisture analysis, degree of polymerization assessment, frequency response analysis and mechanical oscillation monitoring [46]. In [47], the return voltage measurement was proposed to assess the moistening and ageing of the oil-paper insulation system. Table II presents the detection methods of different failure modes. In recent years, more trials have been made to integrate machine learning tools with the above detection methods. In [48] the authors discussed the application of Bayesian to model the embedded expert knowledge and to learn the data patterns in the DGA data. Multiple classification methods are used [49] to predict the health indeed evaluate oil samples' health condition. In [50], the author investigated twelve machine learning algorithms to classify the operating conditions of one thousand transformers' data. The common issue of missing data was discussed in the paper as well. The report [23] gives detailed guidance on how to conduct intelligent condition monitoring for power transformers. Applications are presented, and discussed the possibilities using algorithms like fuzzy logic, neural networks, expert system, etc. With deep learning developing fast and being widely employed, fewer applications are not discussed yet in the condition monitoring of power transformers, which will be explored in this study.

Table 23 Condition monitoring methods for power transformers [41]

Condition monitoring methods	Failures
Dissolved gas analysis	Partial discharges, discharges of low energy and high energy, thermal faults, carbonization of paper
Partial discharges direction	Weakness in the insulation system
Moisture	Moisture
Frequency response analysis	Winding deformation and displacement, core deformation and displacement, faulty ground core
Oscillation analysis	Mechanical changes, DC-driven effects
Degree of polymerization value	Loss of life
Return voltage measurement	Insulation weakness

In this case, study operation data and deep neural networks are used to identify underlying operational risks for high-voltage equipment condition monitoring. Compared with the previous studies, the study aims to explore deep learning methods to evaluate health conditions and monitor behavioural changes with operation time.

b) Expert knowledge of condition monitoring of power transformers

Condition-based monitoring typically relies on expert knowledge to evaluate and classify the degradation. This study involves the mock interview of power transformer experts from both industry and academia to share their valuable insight on the asset management situations of power transformers. The interview uses the IEC 60812 failure modes and effects analysis [51] as the guidelines for designing the questionnaire, which consists of failure modes, effects and securities, root causes, detection methods and maintenance actions. The summarized results are shown in Table 24. The failures can be separated into major and minor failures. However, finding the root causes for some failures in actual operations is a dilemma, although there are guidelines to follow. For online detection methods, sensors are installed to measure the values to understand the current situation. However, sometimes the critical signals could not easily sample directly with sensors. In this case, the signals are measured and monitored using the existing sensors combined with domain knowledge, which is the ”soft sensor” method. The equipment can return to operation after maintenance is conducted or can be replaced with a new one.

Table 24 Expert interview results on asset management of power transformers [41]

Failure modes and effects	Root causes for failures	Fault detection methods	Maintenance
1)major outages: over seven days; 2)minor failures: short circuits; insulation weakness; 3)severe failures could induce breakdown; some failures could happen everywhere, like partial discharges	1) failure modes and effects analysis as guidelines; 2) affecting factors: production quality; how the transformer is used; environmental; other external factors 3)impossible to identify the root causes of some failures	1)acceptance tests; 2) online detection methods with sensors: gas temperature, moisture, pressure, partial discharges, etc. 3) soft sensor methods; 4) regular offline inspection programs; 5) frequent follow-up after detected anomalies, like impedance test, oil test etc.	Planned or condition-based maintenance with early indications, like: 1) replace the failed component, 2) regenerate oil 3) tighten the structure to reduce vibration, etc.

c) Mathematical models

The study proposes a fault diagnostics method using deep neural networks and control charts for the condition monitoring of power transformers. This paper applies the unsupervised learning method compared to the previous classification algorithms due to the lack of labelled data for data records. The autoencoders compress the raw data and extract the key features and the recurrent gated unit (GRU) to model the dependencies between normal behaviours of power transformers. Finally, the method employs control charts to generate the alarm to indicate the underlying anomalies. For a detailed mathematical model, description the reader is referend to [41].

A control chart presents a quality characteristic over the sample time, measured or calculated from samples. The control chart typically contains an upper control limit (UCL) and lower control limit (LCL) to determine if the characteristic is in control or not [52]. Several control charts depend on the auto-correlations, variables/attributes, sample sizes, shift sizes, and variable numbers. This study aims to monitor the small shifts in the errors between the estimated and actual continuous features with multiple samples. Hence the exponentially weighted moving average (EWMA) control chart is used as post-processing to evaluate the changes in the errors over the operation time.

d) Data sets

In this case, a public study dataset of a power transformer has been used with a rated voltage of 140/55kV and a rated power of 63MVA [53]. Fig.1 shows the schematic diagram of the power transformer. The transformer has two cooling groups, but the website does not illustrate more information. The dataset consists of two parts, which are operation data and a status report. Nine signals are sampled every minute in the operation data, including top oil temperature and reference value, bottom oil temperature and reference value, ambient temperature, average load, current, tap changer position, and temperature. The status report records the triggered events since 2016. A typical event describes the event type, detailed information, and its main function. It is also recorded when the event was handled, and the correction measure was taken. Table IV shows an example with a sensor error and an alarm triggered simultaneously.

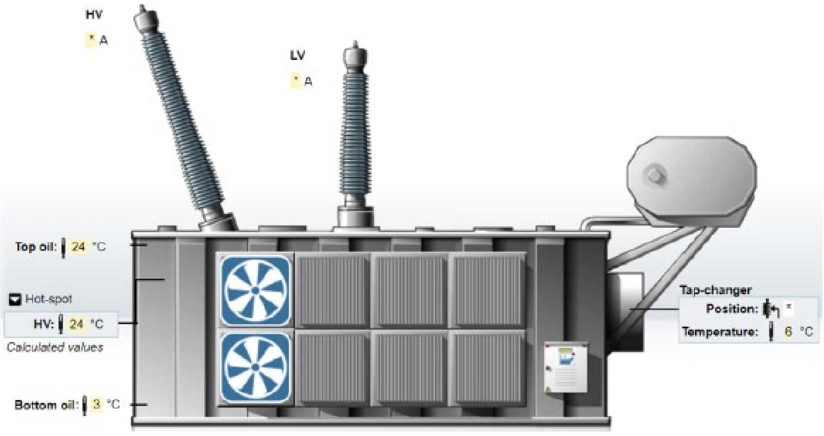


Figure 14 Schematic diagram of a power transformer [41]

Table 25 Example of events in the status report of a power transformer [41]

Handle time	Event type	Function	Description	Measures were taken at
2019-03-10 20:58:27	Sensor error	Contact wear	Tap-changer position	2019-04-17 08:05:50
2019-03-10 20:58:27	alarm	protection	Error on both v and LV sensor	2019-04-17 08:05:52
2019-03-10 20:58:26	alarm	protection	The high voltage winding current sensor	2019-04-17 08:05:52
2019-03-10 20:58:26	alarm	protection	Low voltage winding current sensor	2019-04-17 08:05:52

e) Numerical results

Since the dataset mainly contains temperature signals, this study focuses on the data-driven thermal analysis method. The hot spot is the highest temperature the insulation system is exposed to, directly affecting the transformer's lifetime [54]. In [55] the authors discussed three methods to calculate the hot spot temperature. According to the IEEE loading guides [56], the hot spot temperature Θ_{hs} can be estimated using the top oil temperature Θ_{to}:

$$\Theta_{hs} = \Theta_{to} + K * \triangle\Theta \left(\frac{I}{I_R} \right)^{2m}$$

Where m is the empirical parameter recommended by the loading guidance, and K is the correction factor depending on the manufacturer's design. $\Delta\Theta$ is the deviation of Θ_{hs} and Θ_{to}. I is the load current and I_r Is the rated current. Hence the top oil temperature is the critical signal to indicate the insulation conditions and the lifetime of power transformers. The paper uses four months of data from October 2018 to January 2019 to train the networks. The input signals are the top and bottom oil temperature, the load ratio, the tap changers position and the temperature. Figure 15 shows the part of the input data, and the dashed line denotes the time the sensor error occurred, and the alarm was triggered. The failure happened in the tap-changer position on March 10, 2019. The alarms were released to report high voltage, low voltage, and winding current errors. More information can be found in Table 24. Figure 15 shows that the load ratio returned to zero after the failure. ADAM algorithms train the network with a batch size of 32. The percentage errors PEs between the input and the reconstructed features of the autoencoders are calculated as:

$$PE = \frac{x^{'} - x}{x} \cdot 100\%$$

The PEs are assessed by the EWMA control chart to monitor if the temperatures are out of control. The result is shown in Fig. 3. It can be seen that the EWMA percentage error z varies with the UCL and LCL at the beginning of February. z started to exceed the LCL on February 25 before the sensor failure. According to the expertise, the result may be affected by the operation status of the cooling system. However, the authors could not conduct further analysis in this paper without access to the relevant information, which could be the future work at the next step.

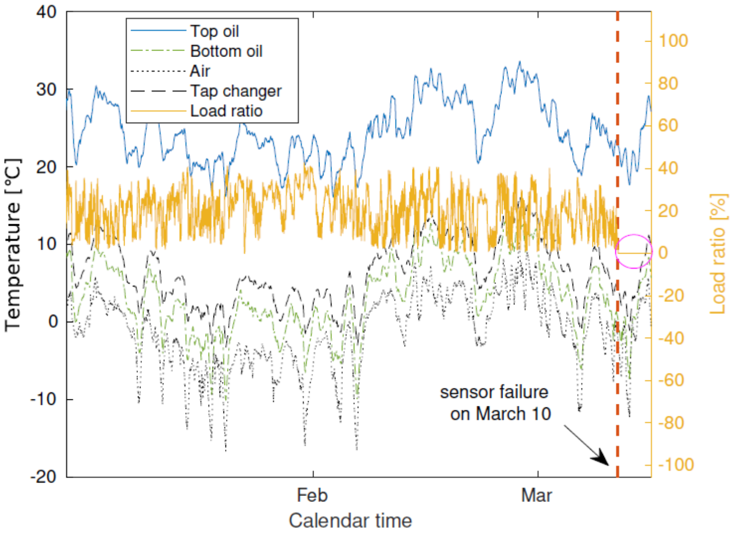


Figure 15 Operational data for the Power Transformer [41]

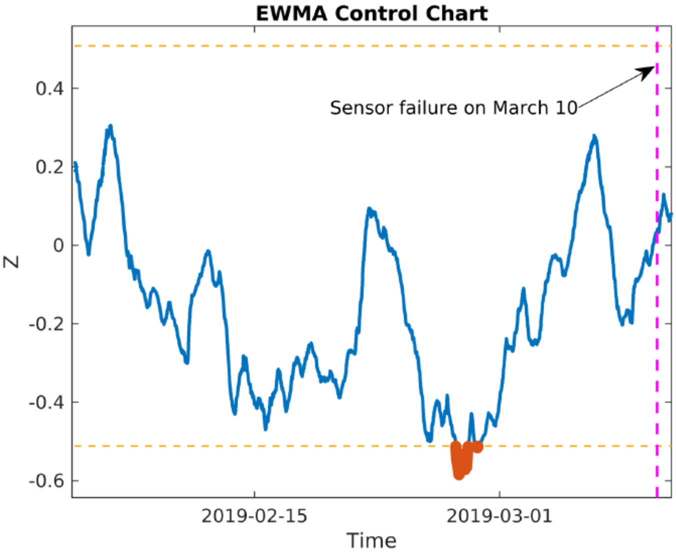


Figure 16 EWMA control chart of the percentage errors of the estimated and real features for the power transformer study [41]

f) Conclusions

This case study develops a data-driven fault diagnosis utilizing deep learning for high-voltage equipment condition monitoring. The resulting approach provides a predictive approach for maintenance and a method for preventive maintenance and input to Stage 2 in an RCAM study according to the previous chapter on systematic approaches for AM.

The proposed approach uses unsupervised learning to model normal operations. The autoencoders are used to extract the key features and the recurrent gated unit to model the dependencies between normal behaviours of power transformers. Finally, the method employs control charts to generate the alarm to indicate the underlying anomalies. The method is tested with an online dataset with sensor failures in the power transformers. The results show that the method can identify the actual failure before the failure happens. Due to the lack of data input, the authors could not integrate more useful information to improve and test the method with transformer failures. These could be further developed in future work.

5.5 Digitalization of Secondary Substations

This case study is based on [57] and the following information was extracted to focus on lifetime extension and to settle possible future actions for asset management.

a) Study of gas-insulated MV switchgear

The study analyzed gas-insulated MV switchgear in secondary substations between 1992 and 2018. Data was collected for the past 12 years, which gave about 3952 reports from around 1 million units, where the oldest installation was located 26 years ago.

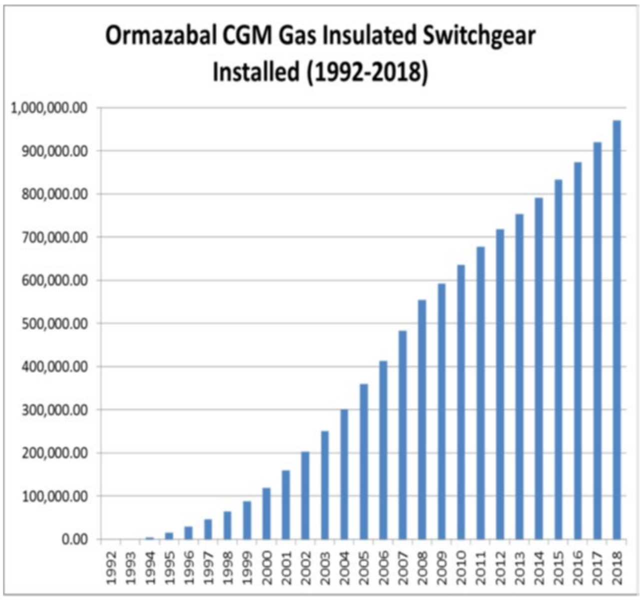


Figure 17 Quantity of analyzed switchgears

The analysis reveals that three main characteristics are critical in the degradation of the electrical equipment, which represents 77% of the total events reported:

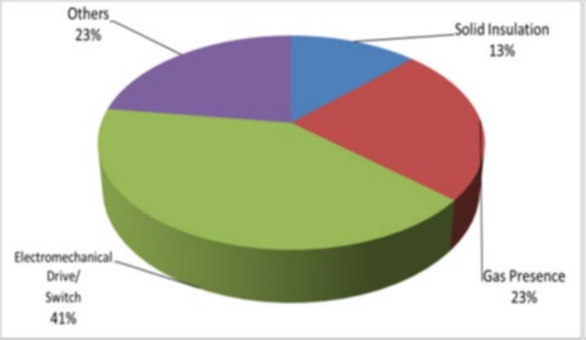


Figure 18 Schematic representation of the error distribution

- **13% are failures in the solid insulation parts:**
  MV connectors, bushings, female bushings, busbar links, fuse holders and incorrect earthing of components on-site

Figure 19 Practical examples of solid insulation failures

- **23% belongs to loss of tightness in the gas tank:**
  Manometer, junction bellows, bushings, welding, fuse holders, switch-mechanism joints, oxidation

Figure 20 On-site display of pressure loss

- **41% caused by moving parts of the switchgear:**
  Mechanical and electrical driving mechanisms, interlocks, motors, closing/opening, buttons, tripping coils, auxiliary contacts, wiring connections

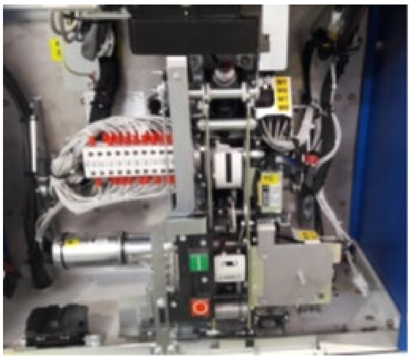


Figure 21 Partial view of switchgear

Not mentioned here are the remaining 23% of the case study's detected failures, like events originating from transport impacts, installation on-site, delivering errors, cable compartment damages and wiring errors in control boxes.

b) Methods to improve the liability of the components

For **solid insulation** surveillance Partial Discharge (PD) measurement techniques are useful to detect problems in the components. These methods are already well-known in laboratory testing or commissioning processes. The challenge is to apply this technology to measure the high-frequency activity on-site and online at the rated voltage of the MV network.

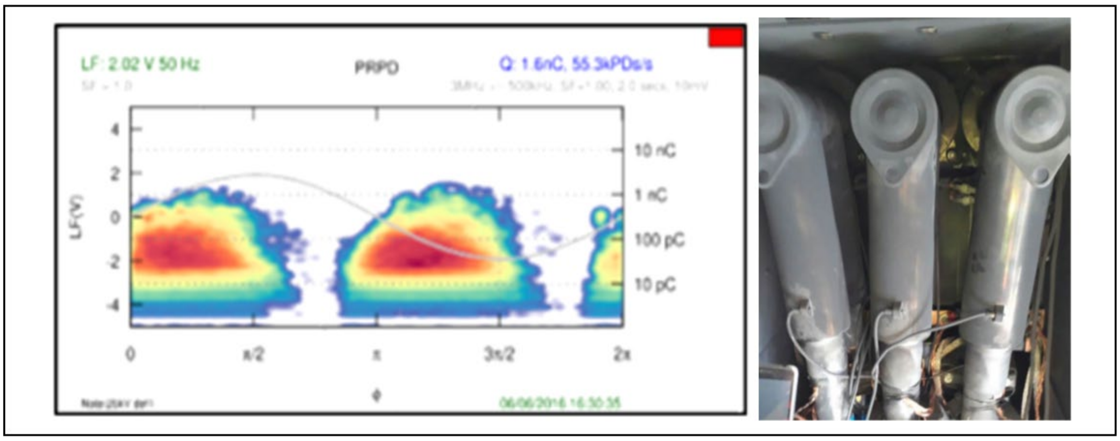
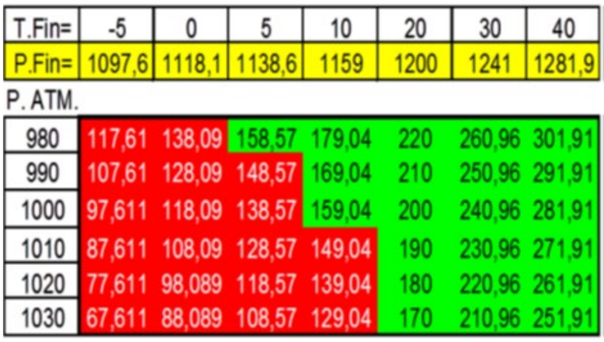


Figure 22 Partial Discharge detection

Results of several tests showed that simple sensors installed in the switchgear could yield measurements directly correlated with the installation's solid insulation quality.
These sensors allow accurate and periodic data about the peak value and the number of partial discharges in the different sectors of the power frequency wave. The data give a periodic and consistent value of this important equipment characteristic.

Regarding **gas tank tightness**, most of the electrical equipment's local indicators of the gas tank pressure are installed. The indication depends on the internal gas, the ambient temperature, and the external atmospheric pressure. The measurements proposed to combine data between the internal and atmospheric pressures and the ambient temperature.



T.Fin=	-5	0	5	10	20	30	40
P.Fin=	1097,6	1118,1	1138,6	1159	1200	1241	1281,9
P. ATM.							
980	117,61	138,09	158,57	179,04	220	260,96	301,91
990	107,61	128,09	148,57	169,04	210	250,96	291,91
1000	97,611	118,09	138,57	159,04	200	240,96	281,91
1010	87,611	108,09	128,57	149,04	190	230,96	271,91
1020	77,611	98,089	118,57	139,04	180	220,96	261,91
1030	67,611	88,089	108,57	129,04	170	210,96	251,91

Figure 23 Indication of limits for pressure and temperature

The sensors periodically send the numerical values of these parameters intending to trace gas evolution inside the tank. The values for the end-of-life would be specified by the switchgear manufacturer and identified in the nameplate to see the health of the equipment regarding this characteristic.
Two types of **sensors** can be considered:

- Auxiliary contacts (moving parts):

  To detect the position of the main switch, earthing switch, cable compartment cover, auxiliary voltage and interlock activation, among other signals.
  Additional measurement features detect the time necessary to operate every opening/closing of the motor-driven mechanism, the time delay when opening or closing among the auxiliary contacts, etc.

- Voltage and current MV sensors (type LPIT):

  It is possible to acquire sample voltage and current values for the last periods of every opening- and closing operation to determine if the electromechanical drive and switch perform correctly.

c) Conclusions

The DSOs are already facing use cases in Smart Network projects, mainly oriented to distribution automation, automatic network self-healing, power flow control and advanced meter management.
The digitalization of the electrical sector and its infrastructure deployed in Smart Network projects are ready to incorporate a new set of data – hardware as sensors to monitor medium voltage and software for processing – to associate the health index of the electrical equipment. It allows the creation of compatible data models to communicate asset diagnosis information over the substations' existing communication network and devices.
Analytic tools and maintenance applications need to be developed at system-level data, using the analysis and possibilities of the previous asset of digitalising the critical factors at laboratory and experimental network levels.
Further deeper studies are needed to determine the exact values for CAPEX and OPEX to demonstrate the economic balance of results and effort.

5.6 Installed base safety upgrade at a power generation station

This case study presents the massive modernization project of a 1990s steam power-generation plant, one of the largest in Italy. Age and limited availability of replacement parts for original medium voltage air magnetic circuit breakers, now in obsolete life cycle phase, even if still supported by regular manufacture maintenance, is an operation concern on such mission-critical equipment. Switchgear's original design is not internal arc classified, and racking operation by a racket lever on the 50kA-rated installation is a potential safety issue. The plant owner tendered breaker replacement to upgrade to the latest circuit breaker technology, providing withdrawable motorized execution for safety and easy maintenance. The project involved supplying and installing 385 new motorized racking circuit breakers, 47 retrofill with standard fused vacuum contactors for the coal belts substations and 41 local/remote station control panels for all modernized substations.

Considering the actual extended operational life of the switchgear, both the RiR and retrofit solutions with current technology and active apparatus embed standard spare parts with all the benefits in terms of availability and delivery terms. The existing non-arc-resistant switchboards, upgraded by onboard motorization with remote control of racking in/out and open/close operations, now provide a safer environment for personnel that can operate the switchboards remotely.

a) Station operation

The original circuit breaker racking procedure into and out of the connected position exposes the operator to a low probability but extremely high consequences risk. Original panel-breaker interfaces, for example, shutter-operation mechanisms, are complex and may become vulnerable to mechanical failures due to ageing, possibly leading to an internal arc (IA). Such racking operation is required when performing breaker compartment physical inspection, swapping, or scheduled maintenance. The original air magnetic design requires to manoeuvre the several hundred kilograms circuit breaker by a racket insertion lever with an open door or, as in this case, by an external mechanism shown in Figure 24 b, detail B, with a closed door (Figure 24 a, detail A), with the operator in proximity. The selector performs open and close commands in front of the panel on the auxiliary circuit compartment door (Figure 24 a, D). The original switchgear from the 1990s, rated 50kA, is not designed to contain the effects of an internal arc, and a traditional roll-in retrofit solution does not change the operation procedure (Figure 24, C).

a *b* *c*

Figure 24: a) Original non-internal arc switchgear, b) original DIARC and c) traditional retrofit circuit breaker racket racking operation

b) Safety upgrade solution

The main requirement for installed base modernization is the capability to operate all switching and racking of the circuit breakers at a safe distance from the switchgear. Two solutions providing motorized racking and remote control options have been designed, completely type tested in the original switchgear at an accredited laboratory and then installed, replacing over four hundred breakers at the site.

A new local control panel is installed in each substation providing local/remote function, as shown in Figure 25 b. In "remote", control is provided from the plant DCS system, while in "local", racking and switching off the circuit breaker is done from the substation control panel in a safe location far from the switchgear. Maintaining a safe distance between personnel and equipment during critical operations provides the most effective means of avoiding injury by keeping people out of harm's way.

Motorized racking retrofit circuit breaker

Roll-in Replacement (RiR) retrofit solutions (Figure 25 a) can replace obsolete circuit breakers with current production versions, mechanically and electrically engineered to adapt to the existing switchgear. The new retrofit breaker replicates all interfaces to the panel, providing a significant degree of renovation and higher reliability, ensuring the new units are fully interchangeable with the original ones. Embedding a motor-operated racking system onboard each retrofit breaker immediately makes the remote racking function available. It is suggested for often-operated applications or racking from a control centre.


a) b)

Figure 25: a) innovative motorized racking retrofit circuit breaker, b) local substation switching and racking control panel

Retrofill or hard-bus retrofit

Retrofill is a switchgear modernization process that replaces the original circuit breaker with a standard withdrawable circuit breaker by installing a fixed frame that provides the new circuit breaker interface. An additional power circuit connects to the original bushings on the primary disconnect elements. Such a solution can greatly upgrade the switchgear safety performances as it replaces many of the original panel parts, like the shutter and shutter operation system and all relevant interlocks in addition to the circuit breaker. The frame hosts a new circuit breaker standard product and provides racking motorization as an option.

Retrofill requires a longer bus outage when compared to RiR direct replacement due to the original switchgear cell modifications needed to accept the hosting frame and new circuit breaker.

The power generation plant modernization adopted a mixed solution strategy, driven by possible shutdown periods and type of load/operation requirement. The group 3 and 4 steam generation and desox substation breakers have been replaced by the RiR solution with motorized racking, requiring a lower installation time, while the identical air magnetic breaker used to operate coal fuel conveyor belts have been replaced by the retrofit solution with fused vacuum contactor, better suited for the high number of switching cycles required by the application.

c) Retrofit solution

The existing circuit breaker compartment upgrade to support the new motorized racking requires the installation of two fixed reference points on the cell sides, as shown in Figure 26 a, detail A, enabling the retrofit circuit breaker locking in the test position. Locking and unlocking to the new cell anchoring points is operated by the new truck release handles, as in current circuit breaker production (Figure 26 a, C). The racking operation is then possible by the motorization, with a closed door and far away operator or, in an emergency, is still possible as a manual operation using a manual rotary racking directly on the circuit breaker truck racking shaft, shown in Figure 26 a, detail C, during breaker racking travel.

The racking mechanism is derived from standard production withdrawable circuit breakers and hosts all standard auxiliary functions such as racked-in/out position contacts, locking magnets and the racking motor. An umbilical cord and plug connect the circuit breaker to the original switchgear auxiliary circuits (Figure 26 a, D). At the same time, the motorization circuitry and forward/reverse power contactors are hosted behind the circuit breaker top shield to avoid heavy modifications to the low-voltage compartment and for easier integration.

a) *b)* *c)*

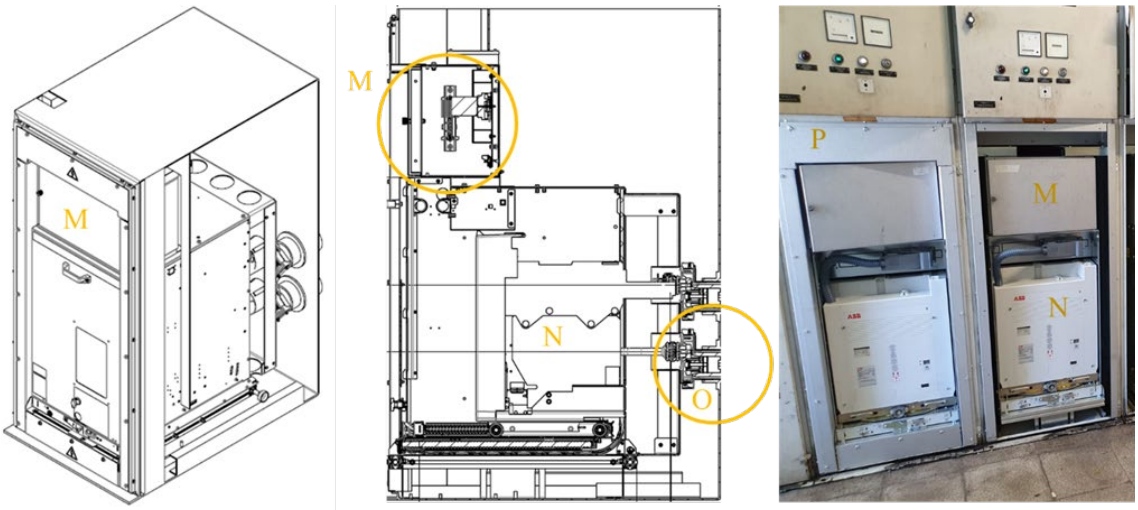
Figure 26: a) Innovative motorized racking retrofit circuit breaker and compartment b) before and c) after modifications

d) Retrofill solution

The plant is connected by a conveyor belt system to the coal terminal in the nearby industrial port, at about 12 km distance, with several towers that enable switching and control of the belt medium voltage motors. The load requires a very high number of switching operations, up to about 2000 per year and with original air magnetic breakers and traditional retrofits, was requiring a significant maintenance effort. In the confined space of the belt switching towers, the need to often access the switchgear and breaker for maintenance operation; therefore, the remote racking option is again a major driver in the modernization. It was decided to use fused vacuum circuit breakers, better suited for the small motors' high switching cycles.

The retrofill solution enables to use of a standard vacuum contactor, shown in Figure 27 b) and c), detail N, adapting the switchgear original circuit breaker compartment by permanently installing the new hosting frame and providing a standard breaker interface by an adaptation copper path to new apparatus power disconnects, Figure 27 b), detail O.

Also, in this application, to limit the impact on the low voltage compartment during installation, all the motorization circuitry and forward/reverse power contactors are installed in a new auxiliary circuit compartment, positioned on top of the retrofill frame, still in the original circuit breaker compartment volume, shown in Figure 27 detail M.



a) b) c) d)

Figure 27: a) Retrofill solution in the original cell, b) section, c) completed and d) during installation

The new vacuum contactor is connected to the new frame by a standard interface made by an umbilical cord on the apparatus side and plug on the frame side, visible in Figure 27 c, below auxiliary compartment M. In this case, it is possible to host all open-closed status and service-test position auxiliary switches onboard the new contactor, thus removing original cell TOC and MOC for easier integration and complete function renovation.

The retrofill solution, concerning the roll-in-replacement one, provides additional upgrade features concerning the internal arc. The solution has not been type tested but is designed to improve the Front side performance characteristics in an internal failure event.

The original switchgear door (Figure 25 a) stays the same with the new motorized racking, and it is an obsolete design, with only two hinges and one locking point, with no structural stiffeners. In an IA event would most probably burst open or even fly away.

The retrofill solution removes that door and replaces it with a frame and a door (dead front cover), Figure 27 a, that provides 5 retention points and two interlock latches, all working perpendicularly to the pressure force on the door.

Due to the new frame and apparatus size, the volume in the circuit breaker compartment for the arc energy expansion is higher for the same ratings. The original door surface is now subdivided into three areas, the door, about half of the original surface and better retained; the low voltage compartment (Figure 27 detail M), bolted to the frame and with a solid steel structure, the metal completion filling the gap all around the frame and the original compartment entry space, solidly bolted to the original frame.

IA event hot gas and by-products will find a higher resistance on the front side and a natural escape route by the vertical chimney design used to discharge the air magnetic arc blast in the original circuit breaker operation. The existing non-arc-resistant switchboards, upgraded by onboard motorization with remote control of racking in/out and open/close operations, now provide a safer environment for personnel that can operate the switchboards remotely.

5.7 Silicon Injection Rejuvenation Technologies for High- and Medium Voltage Cables

a) Background

In some cases, there is a possibility of extending the lifetime of existing equipment by physical interventions, which may eliminate previously developed degradation. In the case of high- and medium-voltage, polymer-insulated cables, injecting specially designed silicon fluids is an available technology.

One early cause of medium and high-voltage cable failure was water treeing [2] [58]. The water trees develop in the insulation of the cables in the presence of water, dissolved salts and alternating current stress, especially in the case of an inhomogeneous electric field where locally, the magnitude of the electric field could be many times its original value [59].

The presence of water changes the dielectric loss and the conductivity. It was realised early on that in many cases, the negative effect of the water tree (e.g. on dielectric strength) can be counteracted without removing and replacing defective cable parts by using chemicals that react with the water present, and the resulting materials have an electrical insulation performance comparable to that of the original insulating material. These include, for example, difunctional organosilanes/siloxanes, which react with water to form polysiloxanes and fill the cavities.

Methylphenyl dimethoxysilane is a relatively cheap, liquid compound, available in large quantities that can be pumped into the cable and spread in the gaps between the conductor and the insulator. Of course, methylphenyl dimethoxy silane is not the only suitable compound. The hydrolytic reaction rate can be controlled by choosing the alkoxy group's size: the shorter the alkyl group, the faster the reaction.

Increasing the temperature will always speed up the reactions, but we have limited possibilities to do this with cables. The temperature of the cable is determined by the environment when it is offline - and cable repair is usually carried out offline.

As with temperature, using various catalysts accelerates the reaction speed by reducing the activation energy. Two groups of catalysts that accelerate the reactions of condensation cross-linking siloxanes are worth mentioning: organotin compounds and tertiary amines. Given that neither organic tin compounds nor small-molecule tertiary amines are environmentally friendly and that during cable repair, the used solution may partially leach into the surrounding soil and contaminate drinking water sources, it is advisable to use catalysts that are also incorporated into the polymer being formed. An example is triethoxyaminopropyl silane, which has an amino group that acts as a catalyst but is also incorporated into the polymer through the ethoxysilane group. Solutions are also known where, in addition to siloxanes, other organometallic components are added to the repair fluid mixture, in particular, titanates (e.g. tetra-ethoxy or tetra-isopropoxy titanate) [60] [61], which also react faster than siloxanes and have a catalytic effect on the reaction.

b) Products

The first silicone injection rejuvenation technology in the 1980s was based on the use of methylphenyl dimethoxy silane, followed in 2006 by the high pressure sustained pressure rejuvenation technology and in 2008 by the increased temperature thermally enhanced rejuvenation technology.

Solutions in the early days:

- 1984 – Acetophenone, standard voltage stabiliser in high voltage cables, a decomposition product of dicumyl peroxide (ran out, had to be replaced).
- 1989 – Phenylmethyl dimethoxy silane (PMDMS) + titanium (IV) isopropoxide (0.2%) as condensation catalyst.
- 1994 – Technology 841a, better dielectric behaviour, led to the technology's spread.
- 2002 – Technology 841a caused Al-corrosion. Thus it was replaced in 2005 by 841b.

A more advanced product, the liquid "732", contained new components that partly reduced partial discharge, had a voltage stabilizer and antioxidant effect, and provided ultraviolet protection. The liquid "732" is oligomeric and therefore has a higher viscosity than methylphenyl dimethoxy silane, but it also decreases in viscosity with increasing temperature. The “732” repair fluid is more expensive and worth using in more developed countries.

However, these repair fluids are not well suited for silicone-insulated cables, but even for EPDM cables, different solutions have to be used then for XLPE cables [62].

c) Filling parameters

Using the psi pressure unit, which is used in American engineering (14.5 psi = 1 bar), three pressure ranges are distinguished for filling cables: below 50 psig is called low pressure (psig is the unit relative to the external air pressure, psi is the so-called "absolute" pressure, which can be measured relative to vacuum), between 50 and 500 psig is called medium pressure, and between 500 and 1000 psig is called high pressure. Increasing the filling pressure somewhat improves the measured puncture strength after repair, which is related to the fact that at higher pressures, the cracks are more filled, and the repair fluid is likely to penetrate better into the water-filled bladders.

It is important to remember that water must be neutralised not only in cracks but also in closed cavities that do not pass directly through channels, i.e. it is not just a matter of flow but also of diffusion through the polymer film.

For a while, increasing the filling pressure improves the dielectric strength of the cable. However, the filling pressure is limited by the mechanical strength of the cable. The pressure used for filling should be chosen according to the cable type and the conductor's cross-section. For example, XLPE cables are more resistant to overpressure because of their cross-linking.

Filling and reaction speed can also be accelerated by heating the cable with a lower current after switching off the high voltage. This reduces the viscosity and increases the size of the gaps through which the repair fluid can flow due to thermal expansion.

d) Result of the Rejuvenation Process

In one study, cables were subjected to artificial water-tree ageing. One part (A) was tested without repair, and another part (B) was injected with siloxane titanate and tested afterwards. The repair fluid + water reaction was also directly observed. First, turbidity was formed, then the precipitate was formed, agglomerated, and then turned into a homogeneous material. Condensation took place after one week, and a yellowish solid was formed after one month.

It was found that the high dielectric constant of the water prevailed at the beginning of the measurement, and the dielectric constant of the mixture with siloxane was still relatively high. As the siloxane reacted with the water and gradually transformed into polysiloxane, the water molecules decreased, and the dielectric constant dropped significantly.

With the decrease in the amount of water (which leads to high conductivity with proton jumps and high mobility), the conductivity decreases by more than an order of magnitude.

Samples A (untreated) and B (treated) were subjected to electrical and thermal ageing to investigate the evolution of dielectric loss. It was found that the loss in the repaired cables drops during the treatment and increases later but remains much lower than in the untreated reference samples.

The extent and mode of water tree growth for samples (A) and (B) were investigated comparatively:

> In case (A), after electrical/thermal ageing following water tree pre-ageing, a highly discoloured layer is formed in the inhomogeneous space, and water tree growth continues unhindered.
>
> In case (B), a discoloured layer is also formed, but the tree propagation is slower at the apex of the wet tree.

The figures below show the Weibull diagram of A and B samples 6 and 13 years after repair [63]: It can be seen that even after 13 years, the electrical strength of the improved cable is still significantly better.

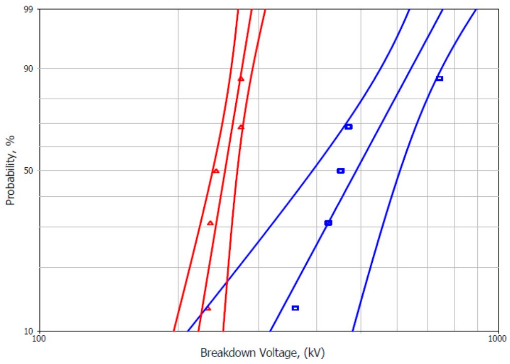


Figure 28 Weibull plot of treated (blue) versus untreated (red) after 6 years. At the 50% probability, the untreated had a breakdown of 150 kV versus the treated sample at 350 kV.

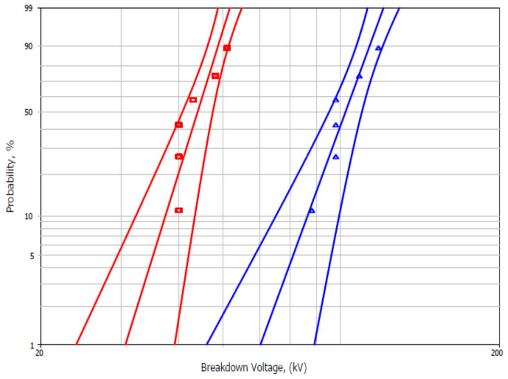


Figure 29 Weibull plot of treated (blue) versus untreated (red) after 13 years. The treated cable still has more than double the breakdown strength left in this case.

e) Summary

Silicone rejuvenation technology is now a mature and available technology. If the cable type allows, and ongoing water treeing is suspected, it is worth considering using this method. Naturally, the value of the expected lifetime gain need to be compared with the repair cost.

5.8 Influence of storage on condition of spare bushings

Spare parts are often held in stock to ensure a quick repair or overhaul of important electrical equipment. However, the equipment in service and the spare parts are subjected to ageing. Adequate storage can slow down this process, ensuring the proper condition of spare parts. The following case study is extracted from a master thesis [64], focusing on the influence of adequate storage on the ageing of bushings for power transformers. The following examples were measured on the state-of-the-art 110 kV RIP (resin-impregnated paper) bushings.

The dielectric response was measured to assess the condition and estimate the insulation's ageing. The dielectric response curve consists of the loss factor tan δ, recorded in a wide frequency range. It represents the dielectric losses of an insulation system and is affected by several factors, including ageing [65]. Generally, identical insulations in similar conditions will have a similar dielectric response. Higher tan δ and, therefore, higher dielectric losses indicate a worse condition.

a) Comparison of Recently Removed Bushings with Spare Bushing

Six bushings (DF_1 … DF_6) were investigated, manufactured in 1993 and mounted on power transformers in service for about 25 years. In parallel, a reserve bushing DF_24_Res was stored without sealing in a wooden transport box (Figure 26). After removing the service-aged bushings from the power transformer, the dielectric response of all seven bushings was measured to compare their condition.

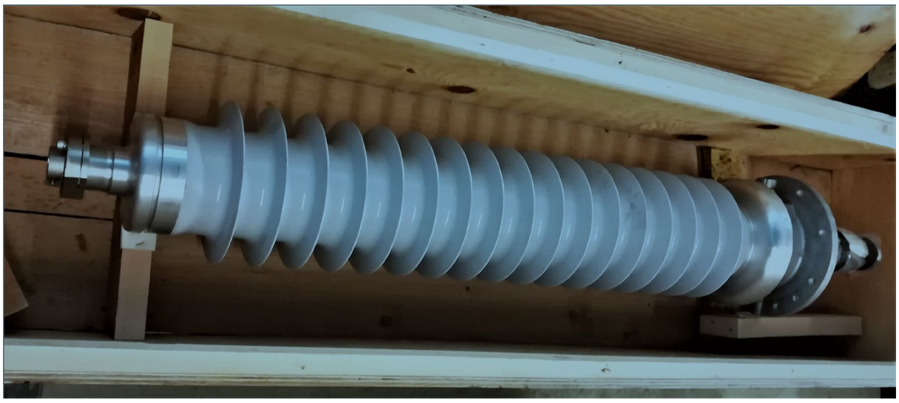


Figure 30 photo of the reserve bushing, stored in a wooden transport box

The dielectric response of all DF_1 … DF_6 shows very similar behaviour, suggesting a similar insulation condition. The tan δ at 50 Hz is between 0,4% and 0,5%, which is acceptable. However, the reserve bushing DF_24_Res, which has never been in service, shows higher, unacceptable values (Figure 27). This behaviour indicates a worse condition compared to the service-aged bushings.

The increased dielectric losses are probably due to water ingress and possible delamination due to the storage in the wooden transport box without sealing. The other six bushings were mounted and therefore sealed by the transformer oil. Furthermore, the temperature changes in the warehouse promote water ingress, in contrast to the relatively constant temperature of the mounted bushings.

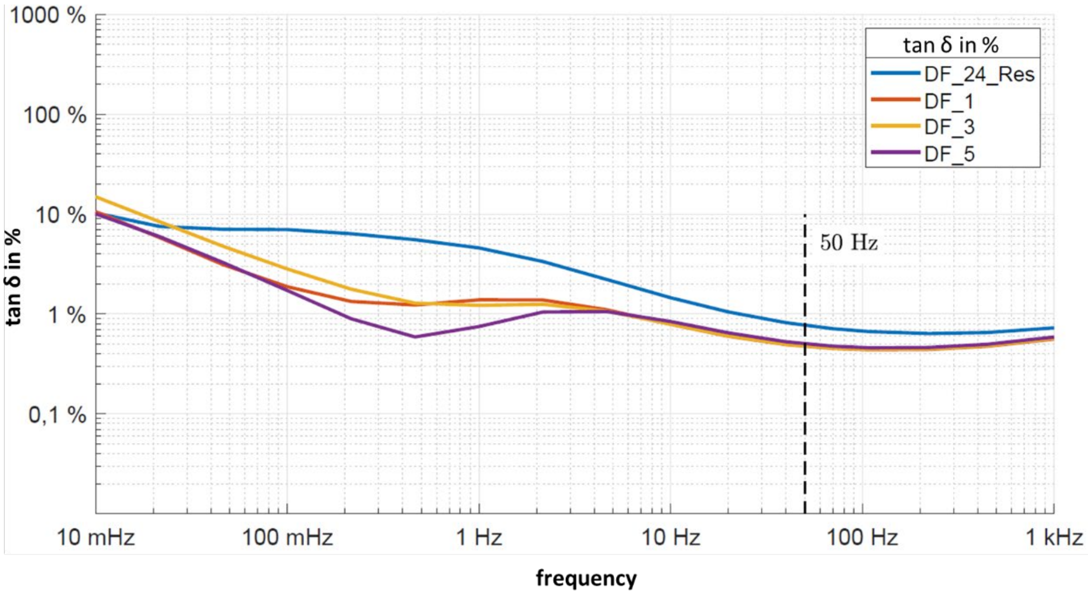


Figure 31 Dielectric response of previously mounted bushings (DF_1, DF_3, DF_5) and reserve bushing DF_24_Res

b) *Investigation after the damage to the sealing*

Five identical spare bushings with consecutive serial numbers were investigated in this second case. They were stored in a wooden transport box for several years, each sealed separately with a foil prohibiting moisture ingress. Before this investigation, one of these boxes containing the bushings DF_21 and DF_22 was damaged, and rodent dung was found. Furthermore, the foil was bitten, breaking the sealing (Figure 28).

The dielectric responses of all bushings are shown in Figure 29. It can be seen that the curves are very similar for four of the five bushings. The relatively low tan δ values indicate a good condition. In contrast, DF_21 showed enhanced dielectric losses, probably caused by moisture ingress and possible delamination.

It could not be clarified why only DF_21 showed enhanced dielectric losses, whereas DF_22 was apparently in good condition, even though the sealing was also damaged. It might be possible that the sealing of this bushing was ruptured later compared to DF_21.

Figure 32 Storage of bushings in a wooden transport box, each sealed with a foil prohibiting moisture ingress

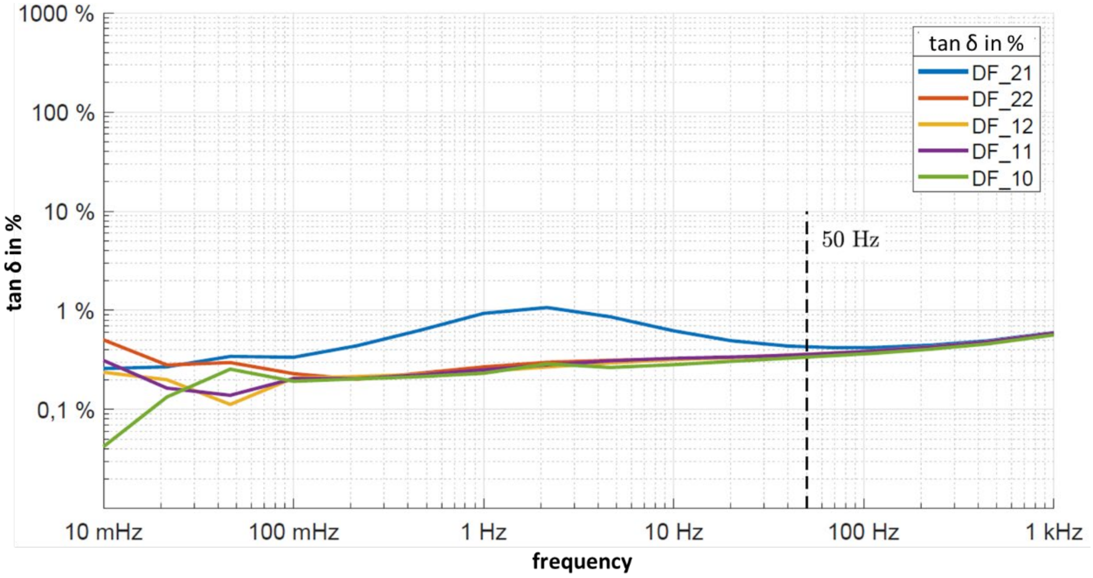


Figure 33 Dielectric response of bushings (DF_10, DF_11, DF_12, DF_22, DF_21)

c) Conclusion

Spare parts were held in stock if necessary to ensure a fast repair. However, they are also subjected to ageing, even without service stress. Consequently, the spare parts are not necessarily in better condition than the equipment in service. Adequate storage, depending on equipment type and storage condition, can help slow the ageing and ensure the condition of the spare parts.

This case study focused on 110 kV RIP bushings. It was shown that unsealed storage over approximately 25 years led to a worse insulation condition than service-aged bushings. The importance of sealing for storage of bushings is underlined by the second case, where a damaged sealing led to significantly increased dielectric losses compared to identical, well-sealed bushings.

6 Summary

The optimal use of equipment lifetime is a target of an asset management process. Within this process, maintenance actions are to be planned. The specific arrangements strongly depend on individual frame conditions and priorities, like maintenance strategy, index values and thresholds for condition assessment, economic priorities, or risk analysis. This report aims to guide realization by summarizing major aspects and illustrating experiences through related case studies.

Due to the high requirements for reliability and resilience of the power network, the lifetime extension options in this report cover the reliable lifetime of electrical equipment, which is usually earlier than the functional end of life. The economic end of life is less important for this report, as the lifetime extension is not necessarily the economically best solution. Lifetime extension might be technically necessary to keep equipment in service while network reinforcement takes place.

The ageing process of equipment differs strongly depending on service load, but other external influences can also lower life expectancy, like environmental stress and other extrinsic impacts. Therefore, a reasonable maintenance strategy should map these major influences. Different maintenance strategies are suitable depending on equipment type, fleet size, voltage level, etc. Corrective, time-based and condition-based maintenance rather refer to electrical equipment. In contrast, reliability-centred or risk-based maintenance has a system focus bases on a strategic process to define thresholds, indices or risk values.

Modernization and retrofitting are common actions to extend lifetime. Refurbishment might deliver a short to medium-term benefit. It does not regain the full lifespan like a replacement but is less cost intensive. Both actions are viable only if the original manufacturer delivers spare parts or replacement units. A retrofit, meaning a modernization with standard devices, could be targeted if this is impossible. However, this is technically not doable in all cases. A Roll-in Replacement could be a solution where the original design is reproduced. Which of these actions is technically and economically feasible and leads to the best benefit concerning reliability is highly individual.

Most maintenance strategies and decisions for modernization or retrofitting depend on a solid condition assessment. A database is needed, created from inspection routines and diagnostic methods. They deliver the necessary background information for threshold or index calculations and help to rank the reliability. There are also various options depending on equipment type, economic feasibility and importance to the overall system. This report tries to give guidance by summarizing often occurring failure modes and methods to detect them by including tables for power transformers, switchgears and cables.

Besides the technical necessity to keep network components in a reliable condition in service for additional time, lifetime extension is also of ecological importance. The circular economy approach mirrors the aim to reduce the environmental impact by “rethink, reduce, reuse, repair, recycle”. Applied to this electrical power system, requirements for future components can be derived: The long-lasting equipment should be designed to be refurbished, repaired or upgraded with low effort, and the used raw materials can be reused. In any case, lifetime extension instead of direct replacement minimizes the environmental impact.

7 Literature

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