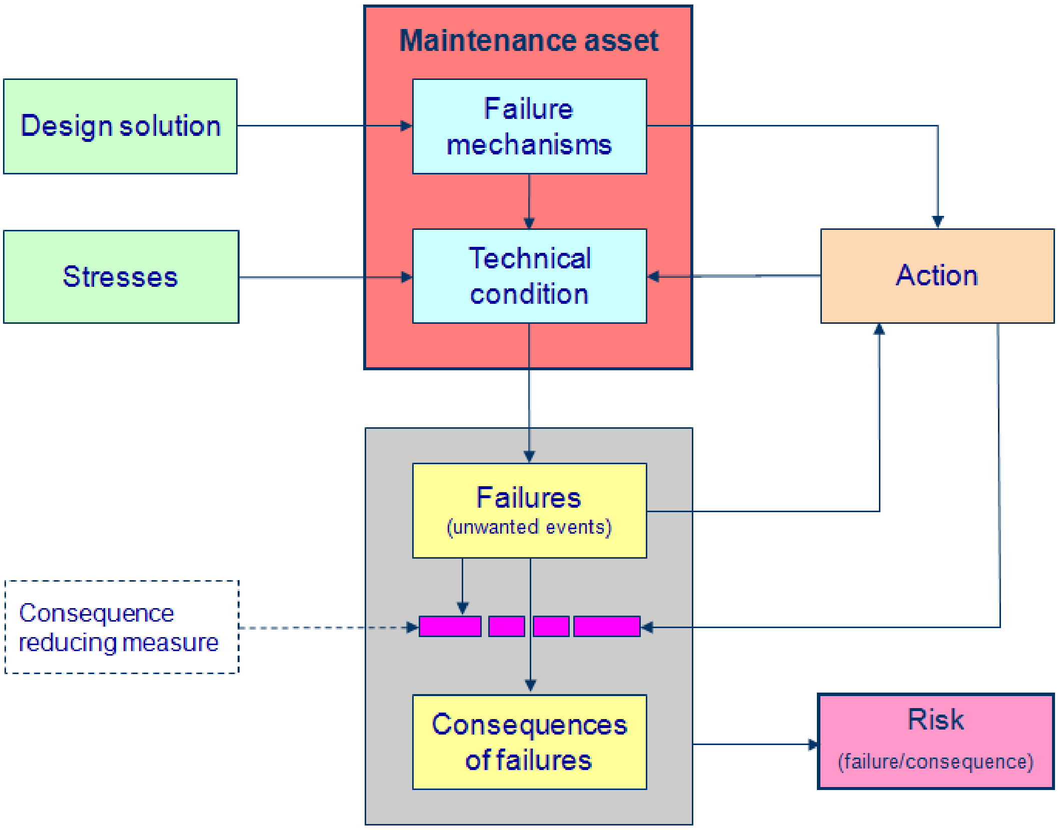
R&D project organized by Energy Norway (2007-2011)

Assessment of technical condition and lifetime of T&D components

- **Methods for condition monitoring/assessment of transmission and distribution components**
- **Handbooks for condition assessment of overhead lines, cables and transformers**
- **Methods and tools for calculation of remaining lifetime, failure probability and risk**



SINTEF Forskningsrådet EnergiNorge

Project objectives

i) To develop and evaluate methods for assessment of technical condition, maintenance requirements and lifetime of components and installations in electric power networks.

ii) To establish methodology and data basis for estimation of residual lifetime, failure probability and lifecycle costs of transmission and distribution components, and develop a software tool for storage, updating and utilisation of lifetime data.

Utilitarian values

The project has resulted in new knowledge and tools for network asset management, and particularly provided new decision support for maintenance and reinvestment planning. This is achieved through development and demonstration of new condition assessment methods and tools, and through new and updated methods for interpretation and utilisation of information about technical condition of components in T&D networks.

In the following short summaries of the technical reports prepared in the project are presented.

Condition Assessment of Electrical Grid Components. Survey of Diagnostic Techniques and Evaluation of Methods. (Publ. 260-2007)

The report gives a comprehensive and compact overview of diagnostic methods used to assess the condition of high voltage components in electrical energy transmission and distribution grids. It presents the results from a literature study and interviews with experts on the different components.

Each chapter contain tables which summarize available diagnostic methods used to assess the condition of the different components, and each method is linked to a known condition descriptor for the component.

The components included in the report are:

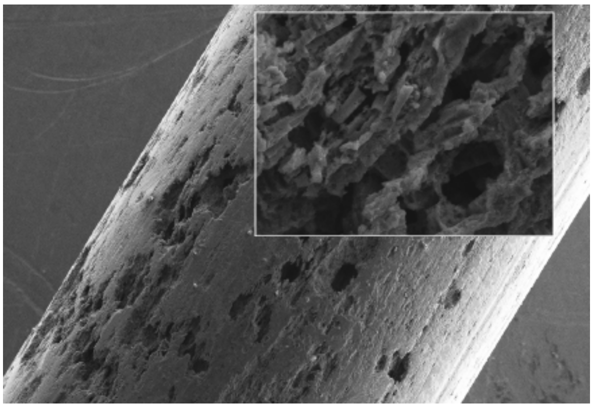
- Overhead lines
- Cables
- Transformers
- Switching equipment
- Capacitors
- Surge Arresters
- Insulators
- Instrument transformers
- Gas insulated substations

The tabled lists of condition assessment methods give an overview of the available methods. Details are given in reference articles in the last column for each method. The reference articles can be technical brochures and articles from objective organisations, e.g. CIGRÉ or IEEE, or also product brochures and user manuals from the manufacturer or distributor of the method.

Inspection of conductors adjacent to suspensions and fittings (Publ. 294-2009)

Common characteristic damages and time dependent deteriorations in suspensions can be recognized as galvanic corrosion, crevice corrosion, pitting, AC corrosion, fretting and fatigue.

- Fatigue can occur at suspension clamps, dead end clamps, spacer clamps, damper clamps, taps and clamps of aircraft warning markers.
- Abrasion and wear occur at loose components on conductors subjected to vibration.



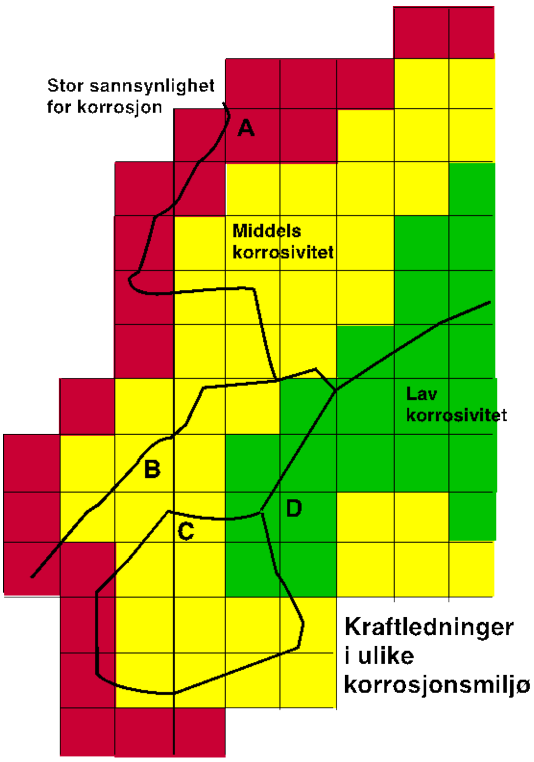
The results clearly reveal the suspension points as locations with enhanced deterioration rate acting as the “weak link” of the conductor. The most commonly used inspection techniques to reveal wear, corrosion and broken strands beneath suspension clamps have been visual inspections, infra red thermography and conductor samples. Resistance measurements have also to some extent been able to reveal broken strands. Measurements of aeolian vibrations can be carried out by means of generic transducers, vibration detectors, optical vibration monitoring devices and specific vibration recorders. The general failure criterion is: Actual load Q > residual strength R, but in Norway it has so far been more common to use a deterministic exclusion limit of 30% decrease of the tensile strength of the aluminium wires. Estimates of absolute values for the residual life of conductors in years should be viewed as indicative approximations expressing degradation and vibration severity.

Refurbishment of conductors in power line transmission systems (Publ. 329-2011)

The most important reason for repairing damage to a conductor is the need to improve reliability and extend its life. The alternative is to replace a conductor with a new one to restore the expected lifetime. Reports from users describe how the use of repair rods, helical protection wires, long clamps, vibration damping, spacers, replacement of insulators, clearing power line routes, replacement of all or part of the conductor, or shunting damaged conductor sections have succeeded or failed in preventing conductor failures at or near the suspension point.

Estimating the service lifespan of conductors in corrosive environments (Publ. 333-2011)

This study takes as its starting point a test scheme for the collection of lifetime data, an empirical model for estimating the lifetime of conductors and an analysis of conductors from actual operation and accelerated corrosion tests. By using the empirical lifetime model to estimate the further degradation of conductors in a span, our results from field samples show that the lifetime of ungreased steel aluminium conductors has a significant correlation with the corrosivity of the marine atmosphere. Lifetime estimates from the accelerated corrosion tests of FeAl number 35-6/1 show a good correlation with the field samples that were assembled for this project. Conductors with a large cross-section have better “corrosion resistance” than thin conductors in exposed coastal zones.

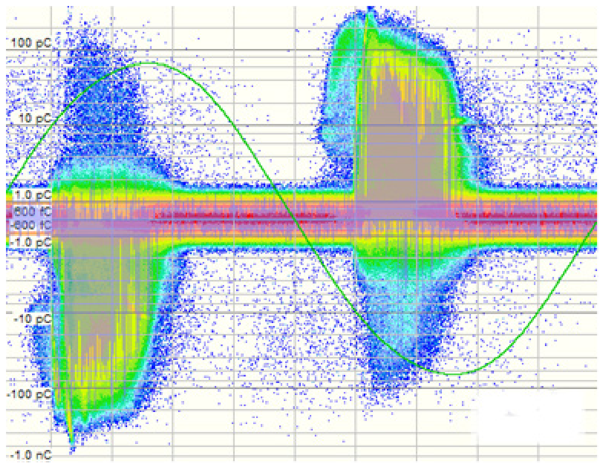


Overview of problems related to various cable types and cable equipment (Publ. 314-2010)

The report contains a systematic overview of types of cables and associated equipment, and the problems that have been observed for the various components over the years. Background information for the development of cable technology in Norway for 12 and 24 kV cables is presented. Both MIND and XLPE cables are briefly described, and various types of cable accessories for XLPE cables are also described. Then the aging mechanisms and typical failure types and failure mechanisms that occur for the various components and existing operational experiences are explained. Examples of various diagnostic methods that can be used for the different components are also given. Finally, a chapter on high-voltage cables and equipment are included.
(This report is written in Norwegian)

Condition assessment of medium voltage XLPE cable systems installed in the 1980s (Publ. 331-2011)

Generally, the failure statistics of medium voltage XLPE cable accessories in Norway show that the overall failure rate is relatively low. However, for some types of joints and especially those installed in the 1980s, the insulation resistance is becoming very low and such joints have also started to fail. The mechanisms for these failures are yet not fully determined. This work includes both on-site and laboratory characterisation of actual joints. During on-site condition assessment of the cable link, low resistivity values and partial discharges were detected. Then a selected three phase cable was removed from service, shipped to and further analysed in the laboratory. The joints were characterised by dielectric spectroscopy in frequency domain, DC resistance and measurements of partial discharges.

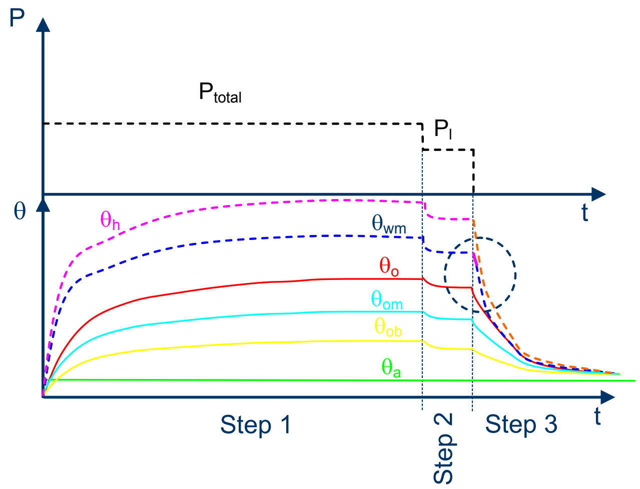


The results show that the low resistivity of the joints as well as the partial discharge activity is likely due to the water sorption during service. Drying strongly reduces the dielectric losses and permittivity, as well as extinguishes the partial discharges. Rewetting does however not re-establish the discharges.

On-line monitoring of power transformers (Publ. 332-2011)

Extension of the useful life of power transformers is the single most important strategy for extending the life of power transmission and distribution infrastructures. Continuous assessments of transformer operating conditions accomplished through on-line monitoring, off-line diagnostic test, expert system diagnostic and analysis modules existing and under development, are examples of the practical implementation of that strategy.

Undoubtedly, the winding hot-spot temperature is one of the most critical parameters that defines the power transformer overloading capability and the aging rate of the oil-paper insulation. Therefore, in order to provide more accurate corresponding transformer assessment tools the IEC 60076-7 thermal and loss of life models are reviewed and improved in this report. A practical application example of the models is given. Also, the ageing kinetics of the transformer insulation is discussed and application procedure established considering the latest research findings.



Methodology for establishing life curves based on condition monitoring data and expert judgments (Publ. 310-2010)

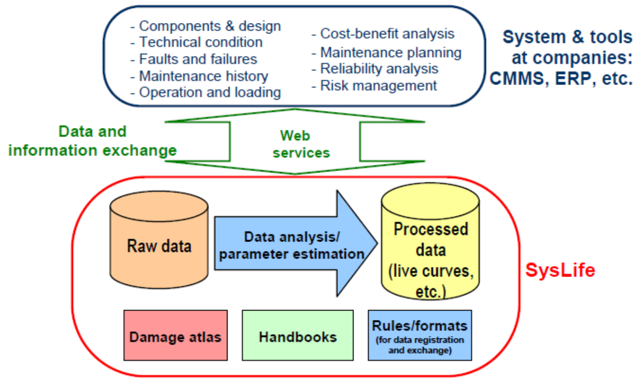
Remaining lifetime and probability of failure of components in the power system are important issues for planning of maintenance and refurbishment. The concept of life curves provides an approach to utilize information about the technical condition (condition states) for modelling component degradation and for calculation of remaining lifetime and failure probability. This technical report describes methodologies for establishing life curves based on condition monitoring data and/or expert judgement. The methodologies presented in this report can be applied for different types of components and failure mechanisms. Thus, life curves provide a generic approach for degradation and lifetime modelling.

The report describes methodologies that can be used to established life curves based on different sources of information, such as judgements provided by one or several experts, or condition monitoring data. Furthermore, establishing life curves using a combination of expert judgments and condition monitoring data is also described. Because different failure mechanisms and components are assessed separately by the life curve approach, the report also shows how analysis results can be aggregated. In addition, references are given to tools and software prototypes that can be used to establish the life curves, to calculate failure probability and remaining lifetime, and to aggregate the results.

The report also presents a number of examples of life curves for selected components and failure mechanisms. The examples include different components of power transformers and circuit breakers. Furthermore, a study on water tree degraded XLPE cables and case study on wood poles are presented. These examples show the use of the life curve approach and can be used as basis for an own analysis.
A file is attached to this report where some of the life curve examples are collected.

System for lifetime related data (Publ. 336-2011)

This report is co-written by the project *Value adding maintenance in power production.*



The objective of this report is to provide a preliminary and general description and specification of an information system for collection, storage, processing and reporting of data related to lifetime analyses and maintenance management (SysLife).

The report is the final documentation of the SysLife-related activities in two *projects (Value adding maintenance in power production and Assessment of technical condition and lifetime of transmission and distribution components)*, and serves as basis for further work with SysLife in a new research project – also called SysLife – which follows up the work in the other two projects.

The report provides a detailed overview of the background for SysLife. A preliminary and general description and specification of SysLife is presented. The specification method is also described. Finally, challenges are discussed and recommendations for further work are given.

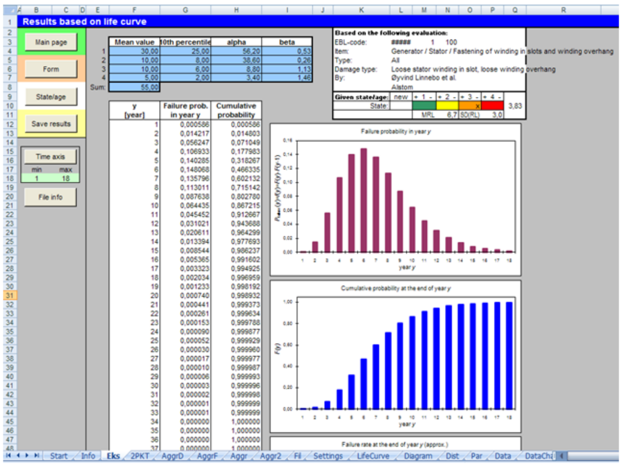
User's guide to Optimal Maintenance Tool Box (Publ. 319-2011)

This report is an updated version of the user's guide for a group of tools that are collectively known as **Optimal Maintenance Tool Box**. The reason for the update is that the tools have undergone further development since the last user's guide was prepared.

The report contains a description of the following tools:

- **Failure probability:** Estimation of Failure Probability (ESTSVS) based on knowledge of a component's technical condition, design, operational conditions, etc.
- **Profitability (NPV calculation):** Calculation of profitability (net present value) of maintenance and refurbishment actions/projects.
- **Qualitative utility value:** Calculation of qualitative utility value (HSE, etc.) based on qualitative evaluation of maintenance and refurbishment actions/projects, including tools for the creation of a decision-making model.

All tools have been developed using MS Excel / Visual Basic and Matlab.

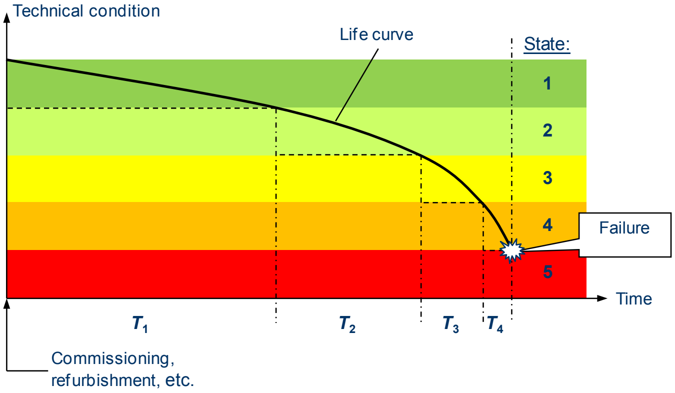


Handbooks for condition assessment

As part of the project, three expert groups have been defining technical condition and described relevant condition assessment methods for different equipment types. The groups have been engaged in the preparation of the following condition monitoring handbooks:

- **Overhead lines** (wood poles and current conducting system)
- **XLPE cables**
- **MIND cables**

The project has also contributed to the development of a chapter on maintenance of **power transformer windings** that is part of a comprehensive maintenance handbook for power transformers prepared by the User Group for Power and Industrial Transformers in Norway.



State	Description
1	No indication of degradation ("as good as new")
2	Some indication of degradation. The condition is noticeably worse than "as good as new".
3	Serious degradation. The condition is considerably worse than "as good as new"
4	The condition is critical.
5	Fault state.

In addition to the technical reports and hand-books, 14 project memos have been prepared.

PhD study

The project has funded a PhD study on the topic "Damage mechanism of aluminium conductor strands used in marine environments". The dissertation will take place medio 2012 according to the plan.

Summary of the work: The damage of conductors, by corrosion and mechanical factors at the clamps, determines their lifetime. Failure analysis work has showed wear, fretting and corrosion or the combination of these as the main failure causes. Therefore, sliding and fretting behaviours of the conductor strands have been further investigated by experimental techniques in different test conditions simulating real service conditions. Sliding wear tests were performed on the aluminium alloy strands in air, tap water drop, chloride solution and under cathodic protection conditions to characterize the material degradation mechanisms in similar conditions. Moreover, fretting tests have been performed to map crack initiation and material wear conditions in terms of normal contact force and displacement amplitude in air and chloride environment. The map can be used as basis for generating data in a similar test condition to predict service lifetime of conductors.

Journal papers

IEEE Transaction on Power Systems:
Using State Diagrams for Modelling Maintenance of Deteriorating Systems
(Welte, 2008)

Journal of Risk and Reliability:
A rule-based approach for establishing states in a Markov process applied to maintenance modelling
(Welte, 2008)

Journal of Risk and Reliability:
Using life curves as input to quantitative risk analysis in electricity distribution system asset management
(Nordgård, Welte, Heggset, 2009)

European Transaction on Electric Power:
IEC 60076-7 Loading Guide Thermal Model Constants Estimation
(Susa, Nordman, submitted 2011)

Conference papers

11 conference papers have been published and presented from the project.

Presentations at seminars and courses

Presentations have been given at 22 different seminars and courses, including participation in the post-qualifying course *Risk based maintenance and renewal of power networks* at NTNU.

Participants

The project has been run by SINTEF Energy Research with Energy Norway as contractor towards the Research Council of Norway. Several of the main Norwegian power utilities, together with EDF R&D in France, REN and the cable producers Nexans and Draka, have participated in the project both with funding and in-kind.

The participating Norwegian utilities in the project were Lyse Elnett, Hafslund Nett, Statnett, BKK Nett, BKK Produksjon, Agder Energi Nett, Eidsiva Nett, TrønderEnergi Nett, Skagerak Energi Nett, Sunnhordland kraftlag, Istad Nett, NTE Nett, Helgelandskraft, SKS Nett and Sira-Kvina kraftselskap.

There has also been cooperation with Elforsk (Sweden) and Dansk Energi (Denmark) through the NorKab group.

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