State of the art - life time modeling and management of transformers

Anna Franzén and Lina Bertling
6 Conclusions

7 Research project problem formulation
   7.1 Life time models ........................................... 28
   7.2 Loading guide related research problems .......................... 28
   7.3 The effects of maintenance ...................................... 29
   7.4 Condition control ........................................... 29

A Data .......................................................... 33
1 Introduction

1.1 Background

This report is the result of a literature study and discussions with Peter Hjalmar, Ulf Lager and Rickard Tjäder at E.ON Elnät Sverige AB, Lena Melzer, Lars Pettersson and Claes Bengtsson at ABB Transformers, at SvK about transformers, their failures, maintenance and life time. The aim with this study is to learn and to formulate research problems for the continued project. The study is made at the end of a learning process within the Ph.D. project “Lifetime modeling and management of transformers” at the school of Electrical Engineering, division of Electromagnetic engineering at the Royal Institute of Technology.

The Ph.D. project is one of two Ph.D. projects about transformers financial supported by EKC. Within the other project “Electrical and thermal modeling of power transformers” Hanif Tayakoli will use transformer modeling to investigate FRA, Frequency Response Analysis.

Lina Bertling has been a researcher and supervisor of the Ph.D. project “Lifetime modeling and management of transformers”. In association with the project Sabina Karlsson has written her master thesis [1].

This project is made within the RCAM group. RCAM stands for reliability centered asset maintenance. The aim with the RCAM method is to develop “optimal” maintenance strategies for a system. The method consists of three stages. The first stage is to identify critical components for the system reliability. The second stage is an analysis of the critical component, its failure modes and preventive maintenance in order to find the relationship between maintenance and reliability. At the end the costs and effects of different maintenance strategies, performed on the critical component, on the system reliability are investigated [2].

In this Ph.D. project the transformer is the critical component and the aim is to develop lifetime models for components based on failure and maintenance statistics as well as measurements, i.e. to perform the analysis in stage two in the RCAM method.

This kind of reliability models for ageing equipment has also been derived for other power system components by for example Bertling, Lindquist and Holmgren.

How the RCAM method has been used on the Birka system, where the XLPE cables were found to be the critical components can be seen in [2]. The XLPE cables were found to break down due to water treeing. A model of the failure rate is given in [3].

Lindquist [4] has modeled the reliability of three different types of power system components based on the knowledge about failure mechanisms, on experiences from the design process, maintenance and on information from condition estimation. The different system components were cables, circuit breakers and disconnector contacts.

Holmgren [5] used Bayesian methods to include an expert’s knowledge about components in a quantitative method to derive lifetime distributions.
Since the aim with the Ph.D. project is to develop quantitative life time models for the transformer section 5 is focusing on different life time models found in the literature. According to the project description the model shall be based on failure and maintenance statistics and measurements. Therefore section 2 pays attention to available statistics. It also describes results from different statistical surveys. In order to decide which component or maintenance action to investigate further it is important to know whether the component fails often or not.

First a short description of the transformer and its parts is given in section 1.2. A description of different failures and their causes follows in section 1.3. All failures can not be avoided or limited by preventive maintenance. For example failures due to sabotage can not be avoided by maintenance. However some failures due to aging of components or parts could be avoided or limited by preventive maintenance. Therefore section 3 is dedicated to aging of the components in the transformer and maintenance performed on transformers is described in section 4.

1.2 The Transformer

The transformer is used in the electric network to convert the power between different voltage levels.

The transformer consists of core, windings and insulation materials. These parts are enclosed and protected by a tank. An on-load tap-changer regulates the voltages. Bushings connect the transformer windings to the net. The core is made of magnetic steel, in order to be able to wear a magnetic field. The windings usually consist of copper strands isolated by cellulose. Oil serves as both isolation material and cooling medium in the transformer. The cooling can be either natural or forced. If the cooling is forced the oil circulation is controlled by pumps. Fans are often used to circulate the air outside the transformer in order to increase the cooling of the oil [6].

1.3 Failures

Different classifications of failures can be seen in the literature. In the Cigré survey [7] the failures were classified by failed components, origin and presumed cause. When the failures were classified by failed components the classes windings, magnetic circuit, terminals, tank and dielectric fluid, other accessories and tap-changer were used. The different origins were mechanical, dielectric, thermal, chemical and unknown. The classes for presumed cause were design, manufacture, material, transport or storage, incorrect erection in site, incorrect maintenance, abnormal overload, overfluxing, lightning, external short circuit, loss of cooling and unknown.

All failures can not be avoided by preventive maintenance. Among the presumed causes, given above, failures due to design, manufacture and lightning can not be avoided by maintenance. However maintenance can increase the transformers ability to withstand overloads and external short circuits up to some limit. Loss of cooling could be avoided by maintenance of the cooling system. Incorrect
erection in site and incorrect maintenance can be avoided by information rather than by maintenance.
2 Failure statistics

Failures can occur due to different reasons. Some failures can be limited or prevented by maintenance others can’t. Some failures depend on degradation processes, which can be used to describe the life time of the equipment, i.e. to construct a life time model - a model for the degradation process leading to failure. Here a resume of failure statistics is given to see why transformer fails and if they fail due to processes that can be used to formulate a life time model.

2.1 Cigré statistics

In order to study the reliability of large power transformers in service, determine realistic parameter values and eventually pinpoint the causes of transformer failures and determine transformer outage times a group called “Transformer Reliability” WG12.05 was formed in 1975. In 1978 the group launched a survey that involved transformers and reactors 20 years old or younger, designed for networks with a highest system voltage of at least 72 kV but without limitations on rated power. For practical reasons the survey was limited to the countries represented in CIGRÉ SC 12 [7].

The received data included more than 1000 failures that had occurred between 1968 and 1978 in a total population of more than 47000 unit-years. From this data failure rates were determined for different populations depending on voltage range, transformer type, age and the presence of OLTC [7].

Difference was made between failures with forced outage and failures with scheduled outage. A failure with forced outage was defined as a failure that caused an immediate need to disconnect the transformer. That is when the transformer is disconnected from the net within half an hour after the failure occurred. If the needed maintenance could be planed to a later time the failure is defined as a failure with scheduled outage [7].

First the failure rates were calculated as a function of winding voltage, types of units and whether the transformer had an OLTC or not. It was found that the failure rate for a transformer generally is in the order of 2% per unit-year. A comparison of failure rates corresponding to different populations showed that the failure rate increase with voltage if no distinction is made between units with and without OLTC. For power station transformers and autotransformers both with OLTC the failure rate clearly increased with the winding voltage, for substation transformers no significant difference was found between different winding voltages [7].

When the failure rate were calculated as a function of the age and the winding voltage it was only for transformers with winding voltage between 300 kV and 700 kV that the failure rate increases with the age. For smaller units the failure rates seems to decrease slowly with age [7].

If instead the numbers of failures are studied it can be seen that 70% of all failures forced an outage. Some diagrams over failed components, origins and presumed causes of the failure, both with forced outage and scheduled outage are also included in the paper [7].
702 failures had occurred in substation transformers. 691 of these failures had occurred in transformers with OLTC and 11 in transformers without.

Figure 1: Substation transformer failures categorized by failed component. Transformers with OLTC. All failures included. [7]

Figure 1 shows that more than 40% of substation transformers with OLTC have failed due to failure in the tap-changer, 19% have winding failures, tank and dielectric fluid, terminals and other accessories stand for about 12% of the failures each. Only 2.6% were due to failure in the magnetic circuit. When only failures with forced outage are considered the only differences are those, the windings stand for 26% and tank and dielectric circuit stand for 8% [7].

In Figure 2 the main origins for all failures on substation transformers can be seen. The origins were mechanical, 53.1%, and dielectric, 30.8% followed by thermal 9.2%, unknown, 5.8%, and chemical failures 1.1%. The origins for failures with forced outage were mechanical, 46.1%, and dielectric, 36.3% the other origins remained on the same levels as for all failures [7].

Figure 3 shows the presumed causes of failures in substation transformers. The presumed cause was unknown in about 30% of all failures, manufacture in 14.7%; design and material stand for 12% each. Incorrect maintenance, lightning and external short circuits stand for 8 to 9% each. The resulting failures were due to transport or storage, incorrect erection in site, abnormal overload, overfluxing and loss of cooling. The differences in presumed causes between all failures and failures with forced outage were small [7].

They also found that substation transformers more often failed due to the OLTC than power station transformers. The reason was assumed to be less frequent
Figure 2: Substation transformer failures categorized by failure origin. Transformers with OLTC. All failures included. [7]

Figure 3: Substation transformer failures categorized by failure cause. Transformers with OLTC. All failures included. [7]
operations for OLTCs and stricter maintenance on station transformers [7].
The total number of failures in substation transformers without OLTC was just 11, the total number of failures in substation transformers was 702. 40% of these, that is 4.4 transformers, had failed due to the windings. If there had been just one failure more or less the distribution between the different failed components had changed a lot. This means that, due to the limited amount of data it was impossible to draw any conclusions about the failure causes for transformers without OLTC [7].

According to the later Cigré study [8] abnormal events like overvoltages and system faults causes more transformer failures than ageing of winding isolation, but the ageing may make the transformer more vulnerable to these abnormal events.

2.2 Elforsk survey

In 2006 Elforsk [9] made a survey about the lifetime of transformers. The survey collected data from 8 Swedish transformer owners about their 130 kV transformers. A Bayesian method was used to evaluate lifetime distributions for different groups, depending on manufacture, of transformers. The amount of transformers, which had reached their end of life, was very low only 3 of 217 transformers. Therefore it was concluded that the used Bayesian method gave lifetime distributions, which were displaced towards longer lifetimes.

2.3 A Finnish survey

A project started in Finland 2002 that among other things investigated the failure rate of distribution transformers in different network systems. The effect of different earthings, network connections and overvoltage protection were analyzed. The detailed results are unfortunately confidential so the paper [10] only presents general results. Despite collection of data from 15 Finnish utilities the amount of data was small. If there had been one failure more or one less during a certain year it had affect the result a lot. When different manufactures were compared it could be seen that one was better and one was worse than the others.

2.4 Statistics from the Commonwealth of Independent States

The Commonwealth of Independent States, CIS is an alliance of 11 former Soviet Republics, Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Ukraine and Uzbekistan [11].

Sokolov et. al. 2005 [12] have studied failure statistics from the ZTZ-Service database, which includes over 5000 large transformers, i.e. transformers rated 100 MVA and above. They have found three main causes of failure. The first cause is weak construction due to for example material defects and underestimation of operational stresses, the second is to high operation stress due to unusual events or operational error and the last is inadequate maintenance and low quality repair, which can lead to critical deterioration of safety margins. Figure 4 shows failure modes for transmission transformers in ZTZ-Service 2000 – 2005.
According to Sokolov et.al. [12] the failure rate of the transformer is high during the first three years in operation, a wear in period. After some years with low failure rate, it raises again after 7 – 15 years due to failures in bushings, load tap-changers and windings. Their conclusion is that the failure profile, in the range 0 – 35 or 40 years, is a combination of wear in failures, random failures and wear out failures of some weak components like bushings and tap-changers. They didn’t find any obvious failures due to paper aging.

2.5 Statistics from North America

In a study [13] of the failure rate of transformers in USA two peaks were seen. The first peak appears during the first year of the transformers operation, due to a wear in period, and the second peak appears after 11-14 years in operation. The second peak in the failure rate was assumed to appear due to lower short circuit withstand capability and/or heating effects caused by the loading of the secondary winding rather than due to thermal aging of the cellulose.

2.6 Statistics from South Africa

Minhas et.al. 1999 [14] present a failure analysis of power transformers in the Eskom network, South Africa, in the range of 88 kV to 765 kV and 20 MVA to 800 MVA. Six failure modes have been identified in the analysis. These are lightning, core problems, tap-changer initiated failures, general ageing, short circuit

Figure 4: Failure modes for transmission transformers in ZTZ-Service in 2000 – 2005. [12]
and others. Others consists of for example bushing, unknown and operational errors.
Figure 5 and 6 show the failures in transformers on $20 - 100\text{MVA}$ and in transformers above $100\text{MVA}$ respectively, were distributed between different failure modes.

According to the analysis [14] most failures in small transformers, $20 - 100\text{ MVA}$, occur due to aging and tap-changers, in medium size transformers, $100 - 400 \text{ MVA}$, the ageing and “other failures” stands for most failures and failures in larger transformers occur due to lightning.

2.7 More about failure rates

The National Grid Company, UK, has found that their transmission transformers have a failure rate of about 0.3% per year and no increasing trend in failure rate with age has been seen since 1971. They also conclude that transformer failures are usually triggered by extreme system conditions like lightning strikes and short-circuit [15].

According to [16] 75% of the failures occur because of bad health condition, such as dielectric problems.

According to [17] the average life of a transformer is assumed to be somewhere between 25 and 30 years and the life span of OLTCs are confirmed to be in the same range as other transformer equipment. The failure rate of OLTCs varies between 0.1% per year in Germany and other similar nets and 3.7% per year in Thailand. Failure reasons have been found to be poor oil quality, high humidity in the oil and over voltages.

In [18] Lapworth studies different hazard rates and their consequences on mean time to failure. His conclusion is that an average failure rate doesn’t estimate a reasonable probability of failure of transformers during their whole lives. A more realistic likelihood of failure would have a low failure rate until some time when the failure rate suddenly increases. For transformers he suggests that the failure rate starts to increase due to damage caused by unusual system events like short circuits and lightning strikes, not due to ageing of paper or oil.

Lapworth [19] also writes that one of the main uses with reliability data is estimation of end of life for the transformer. About end of life assessment and risk management he also writes “The interest here is not so much in the likelihood of experiencing a problem with a typical transformer, but in assessing the likely consequences and risks involved in continuing to operate a transformer which is suspected of being faulty.” Then the aim would be to derive expected values for time to failure and failure costs.

2.8 Conclusions

The statistics from different surveys are hard to compare. Some surveys have classified the failures by failed part others by cause or origin. Some surveys even use a mixture of these classes.

Despite these difficulties some conclusions can be drawn. The references agree that most failures in transformers with OLTC occur due to the OLTC. However
large transformers fail more seldom due to the OLTC than smaller units. The windings seem to be the part that suffers from most failures in transformers without OLTC, and the second in transformers with OLTC.

The main origins for failures are mechanical and dielectric followed by thermal. The main cause is in many cases unknown. When the failure cause is known, manufacture, design and material stand for most failures, followed by operational stresses due to for instance lightning and short circuits in the net and incorrect maintenance. Even though some surveys also mention ageing as a cause of many failures others say that no failures due to ageing have been seen. According to [14] around 30% of all transformer failures occur due to general ageing.
3 Ageing

Even if the statistics don’t show that ageing is a main cause of failure in the transformer, aging can be an underlying cause. For instance aging can affect the transformers ability to withstand short circuits and overloads. In addition one way to construct a life time model is to model the physical or chemical aging processes. Therefore the aging processes for the transformer’s parts are described.

According to the Loading Guide [20] there is no simple and unique end-of-life criterion for the transformer. According to [21] the aging of transformers is related to the ageing of windings, tank, bushings and on-load tap changers. Aubin et.al. [8] agree and state that the transformers lifetime is closely related to its ageing processes.

3.1 Ageing of the windings and it’s isolation

According to [15] the most life limiting component in the transformer is the paper winding isolation. Operating temperature, moisture, oxygen and acidity levels in the oil affects the ageing of the paper. By using standard techniques to evaluate the hot-spot temperature in the windings and relate this temperature to laboratory ageing rates for paper gives that paper lives in about 55 years if there are no thermal design weaknesses.

Even tough the ageing of the cellulose isolation is a time function depending on temperature, moisture content, oxygen content and acid content the model given in IEC Loading guide [20] only uses the temperature as a free parameter. The relative ageing rate $V$ for the isolation exposed to the hot-spot temperature $\theta_h$ in °C is

$$ V = 2^{(\theta_h - 98)/6} $$

(1)

for non-thermally upgraded paper and

$$ V = e^{(15000/110 + 273 - 15000/\theta_h + 273)} $$

(2)

for thermally upgraded paper.

The relative ageing rate is very sensitive to changes in the hot-spot temperature. For non-thermally upgraded paper the relative ageing rate equals 1 when the hot spot temperature equals 98°C if the temperature is reduced to 92°C the ageing rate is halved. For upgrade paper 110°C corresponds to an ageing rate of 1 [20].

The loading guide also gives equations for evaluation of the loss-of-life for the isolation. The loss-of-life $L$ during the time period $[t_1 \ t_2]$ is

$$ L = \int_{t_1}^{t_2} V dt. $$

(3)

As a reference the loading guide [20] says that if the transformer is operated at the hot-spot temperature of 110°C and the isolation is thermally upgraded,
well-dried and oxygen-free, 25% of the isolations tensile strength will remain after 15.41 years.

According to the Cigré working group 12.09 [8] it has been overemphasized to base the expected life of the transformer solely on the ageing of the insulation due to temperature. The reason for the big interest of the isolation lifetime is assumed to be that its material properties are easy to measure in a laboratory and the believe that one or more of the isolations properties can be used to estimate the lifetime of the transformer. The dielectric properties of the paper insulation affect the lifetime of the transformer, but the dielectric strength of the paper is not significantly influenced when the paper is ageing. It has also been found that different properties are affected with different rates, when the isolation ages [8].

The Cigré working group also criticizes that the loading guide assumes that the paper insulation will break first at the hot-spot, due to high temperature failures, and not at the most vulnerable point, due to mechanical stresses [8].

It has been observed that different transformers with about the same age have DP values that differ a lot from each other therefore Jarman et. al. [15] have found that the most critical factor in determining the aging rate of the isolation appears to be the thermal design of the transformer.

If the paper and press board shrinks due to aging it will lead to slack windings with increased risk for short-circuit damage as a consequence [15].

The ageing of windings depends on thermal stresses due to overloads; therefore it depends on the loading history [21].

### 3.2 Ageing of the tap-changer

When the OLTC is operating there are sparks between the contacts. The operational stresses lead to erosion of the contacts and the oil is carbonized due to the sparks. The amount of produced particles depends on the load current and the temperature [21].

### 3.3 Ageing of bushings

According to [21] bushing age due to thermal stresses, that depends on the operating load. A bushing failure leads often to heavy transformer failures; it can even lead to explosion and fire in the transformer [22].

A study in Russia showed that the main causes of bushing failures are old transformer oil and high water content in the oil. The transformer oil ages and breaks down faster with higher oil temperature. An important factor for the formation of water in the oil is the amount of aromatic rings in the oil [22].

### 3.4 Ageing of the tank

The metal in the tank could be affected by corrosion. The amount of corrosion depends on the age of the tank and the maintenance history [21].
4 Maintenance

All failures can’t be avoided or limited by preventive maintenance. However some failures due to aging could be limited or avoided by preventive maintenance. To get a clue of which failures that can be prevented or limited by maintenance today a description of different maintenance tasks performed to transformers today or under investigation follows.

There is a distinction between preventive and corrective maintenance. Corrective maintenance is performed in order to set a failed component back in operation. Preventive maintenance is planned and performed before the component has failed with the aim to reduce the probability of future failure [23].

According to the maintenance instruction [24] most regular maintenance performed on transformers is inspections, tests and cleaning. A common test is dissolved gas analysis DGA of the insulation oil. If there are any leakages, gaskets are tightened, if there is rust on the tank it is treated and painted and the silica gel in the dehydrating breather is changed if it is needed. Further maintenance tasks are performed if tests and inspections show that it is needed. Even if the control equipment is alarming for a failure in the transformer the performed maintenance is based on inspections and tests [25].

4.1 Maintenance for isolation oil

Gas analysis and condition tests of the isolation oil shall be made every year or once in four years, depending on the size of the transformer [26]. Depending on the results from these tests further maintenance are made. Gas analysis tell something about the condition of the transformer, while condition tests of the oil only tells the condition of the oil isolation [27].

If the condition of the oil is under the acceptable limit it can be maintained. The oil can be switched, degased, dried or reclaimed. If the amount of water in the oil is too high the transformer can be vacuum dried, since most water are bounded to the cellulose it is no idea to only maintain the oil [27].

In [28] a new drying method based on the mineral Zeolite’s capacity to adsorb water molecules is investigated. The method is said to be cheap, environmental friendly and able to use in-service. So far has no disadvantages been proved with this drying method.

The transformer can be reclaimed during its normal operation. During the reclamtion the oil passes through podsol filter, where the podsol adsorbs pollutants. Afterwards the oil is degased. Normally the oil passes through the filters 8 to 12 times before the reclamtion is completed. The reclamtion removes in this way acids, which speeds up the natural ageing of the oil, thereby can the reclamtion extend the lifetime of the oil and the transformer [29].

Elforsk [30] made a study of the effects of different maintenance performed on four transformers standing in the same surrounding. The four transformers were subject to different maintenance and their results from different tests before and after the maintenance were compared. The different maintenance tasks were reconditioning, reclaiming, overhaul at the fabric and no maintenance. The
first study was made during 2000 and a second was made three years later in order to investigate the long time effect of the performed maintenance [30], [31]. One conclusion was that the reclaimed oil still showed "new oil properties" after three years. Another conclusion was that three years was a too short time to be able to see changes in the isolation.

### 4.2 Maintenance for OLTC

According to the maintenance instructions for OLTCs [32], [33] the maintenance consists mostly of inspections, measurements and lubrication. The contacts are switched if they are old or in bad condition. The OLTC shall be maintained either after a certain number of connections, specified by the manufacture, or after 3, 6 or 8 years depending on the size of the transformer [26].

To ensure a high oil quality in the OLTC it is important that the oil is dried and filtered. Usually the oil is continually dried by the dehydrating breather, therefore it is important to check and change the silica gel in the breather. The oil can either be filtered continually or at special maintenance occasions. It is also important to check the condition of the contacts and switch them if necessary. Maintenance on OLTCs is made at certain intervals either after a certain number of operations or after a certain number of years [17].

Even if the OLTC stands for a major part of all transformer failures some people say that it don’t fail if it is maintained correctly according to the manufactures instructions [34].

Hällgren and Överbeck [35] derived optimal maintenance intervals for OLTCs from statistical data. According to their statistics preventive maintenance for OLTCs consists of cleaning and lubricating the motor drive mechanism, cleaning and replacing contacts, replacing leaking gaskets and oil filtering. The studied failures have mostly small consequences, like failing voltage regulation, abnormal network voltages and in some cases disconnection of costumers. In many failure cases cleaning and lubrication of the motor drive were enough as repair. The expected total maintenance cost was minimized and an optimal maintenance interval was found to be about 30 000 operation cycles. Due to the increased risk of failures with larger consequences when the maintenance interval is enlarged a new interval was derived with a higher expected consequence cost. The recommended maintenance interval was set to 15 - 20 000 operation cycles.

According to [36] Hydro-Québec developed a maintenance strategy for their OLTCs. The reason to develop the strategy was that two-thirds of their transformers with OLTC are 25 years old or more. Moreover they have found that about 50% of the failures, requiring replacement or transportation to repair shop, occurred due to failure in the OLTC.

The maintenance strategy consists of two procedures. In the first procedure an OLTC family is analyzed based on all failure and maintenance data available for that family. Typical failures and appropriate maintenance tasks are identified and the underlying reasons for each failure are determined. The maintenance tasks are also divided into minor and major work solutions and a cost analysis is performed for the major work solutions. Major work solutions consist of overhaul, replacement and retrofit. Then the second procedure called OLTC
Life Decision Making Process is used on an individual OLTC. The age, number of operations, failure, reliability and preventive maintenance are under consideration. The question is if major work is required on the OLTC or not. If not, minor work is performed and the OLTC is returned to service. To choose the best major work solution on this OLTC the condition of the whole transformer and network planning are investigated. If any major solution extends the life of the transformer to a reasonable cost it is performed, otherwise the transformer is replaced [36].
5 Life time models

Many transformers are replaced when they reach their economical or strategic lifetimes. Economical lifetime is a theoretic concept, and refers to the time up to the replacement time which gives the optimal profit from an alternative investment [37]. When the strategic lifetime of the transformer is out it is replaced because of changes in the power system. The old transformer is no longer suit to transform between the wanted voltage levels either because it is not designed for these voltage levels and currents or the power supplier wants a more reliable transformer in that place [34].

In this chapter the focus will be on life time models, trying to describe the transformers life time in years depending on different measures or a known history of the transformer. Some of the models are indeed models describing the transformers age.

5.1 Life time models not including maintenance

5.1.1 A Bayesian method using Perk’s distribution

Chen and Egan [38] presents a Bayesian method for transformer life time estimation, which uses a simplified Perk’s hazard function and so called Iowa curves. The method can be used on a transformer population with known ages and retire ages on the transformers. Iowa curves or Iowa Survivor curves are a set of 18 curves that can be used to predict retirement patterns of assets. The Perk’s hazard function extends the Iowa curves to a continues spectrum of distribution functions. In their model Chen and Egan use a Bayesian method to find the parameters that gives the distribution function, which describes the data best. Perk’s distribution is said to be better suited to describe data then the Weibull function since it can assume a combination of hazard functions in a single distribution. The Perk’s distribution function is:

\[
f(t) = \frac{e^{\beta t + \alpha}}{1 + e^{\beta t + \mu}} \cdot \left( \frac{1 + e^{\beta t + \mu}}{1 + e^\mu} \right)^{-\exp(\alpha - \mu)/\beta}
\]

and the cdf is:

\[
F(t) = 1 - \left( \frac{1 + e^{\beta t + \mu}}{1 - e^\mu} \right)^{-\exp(\alpha - \mu)/\beta}
\]

where \(\alpha, \beta, \) and \(\mu\) are three parameters and \(t\) is the time.

5.2 Life time models based on the aging of the cellulose isolation

5.2.1 Loss of life based on Loading guide

Weekes et.al. [39] starts with the aging model for the cellulose given in the loading guide [20] and evaluates the insulation loss of life for a converter transformer during the spring and summer months. With coolers the loss of life is found to
be 1.2 days during one day in the summer and 0.3 days/day in the spring. These figures can be compared to 3.8 days/day during the summer if no restrictions on the load are used. If the load is restricted to 90% when the temperature rise above 15°C the loss of life of insulation remains on 1.25 days/day during the summer.

Weekes et. al. [39] suggest that these loss of life calculations can be used, once the owner has decided which risk he wish to take, to decide about seasonal operating restrictions.

5.2.2 Elapsed life based on CO, CO₂ and furfurals

Pradhan and Ramu [40] states that the remaining life of a transformer can be determined by the theory of stochastic processes and that that theory is beyond the scope of their investigation. Instead they have used monitoring data from experiment transformers. From these data a fair correlation between DP value and amount dissolved CO, CO₂ and furfurals in the oil was found. An expression for the elapsed life of the transformer, which depends on an evaluated DP value, is given. The DP value is calculated as a function of the amounts of CO, CO₂ and furfurals in the oil. According to the paper the elapsed life in years is:

\[
\text{Elapsed life} = 20.5 \cdot \ln\left(\frac{1100}{\text{DP value}}\right)
\]

where it has been assumed that unaged transformer cellulose insulation has a DP value of about 1100.

A natural question is if anyone else has used the theory of stochastic processes in order to predict the remaining life of the transformer.

5.2.3 Probability of failure base on the inverse-power-law and Arrhenius model

In [21], [41] and [42] Zhang et.al. presents a lifetime model for electrical systems and uses transformer in a secondary-substation as a component example. The inverse-power-law describes the life of electrical equipment in the presence of the electrical or mechanical stress \( S \). The equation is

\[
L = L_0 (S/S_0)^{-n}
\]  

where \( S_0 \) is a scale-parameter for the lower limit of stress, \( L_0 \) is the corresponding lifetime and \( n \) is the stress-endurance coefficient.

The Arrhenius model

\[
L = L_0 (S/S_0)^{-n} \cdot e^{-BT}, \quad T = 1/\phi_0 - 1/\phi
\]

is a life model for an electrical equipment exposed to thermal stresses due to overheating of insulation materials. \( B \) is proportional to the activation energy for the main thermal degradation reaction in the insulation, \( T \) is the thermal stress, \( \phi \) is the absolute temperature and \( \phi_0 \) is a reference temperature.
If the inverse-power-law is multiplied with the Arrhenius model an overestimation of the total stresses are determined. By introducing a correction factor \((S/S_0)^bT\), where \(b\) is a coefficient depending on the reaction of the material due to combined stresses, a better estimation is found.

The Weibull function

\[ P(t > L) = 1 - \exp(-\left(\frac{t}{L_{63\%}}\right)^\alpha) \]  

(6)

describes the likelihood of failure at given stresses. Determining \(L_{63\%}\) from the multiplication of 4, 5 and the correction factor gives the expression for the probability of failure in 7

\[ P(t > L) = 1 - \exp\left(-\left(\frac{S}{S_0}\right)^{(n-bT)} \cdot \left(\frac{t}{L_0}\right)^\alpha \cdot e^{\alpha BT}\right). \]  

(7)

The assumption is that a failure will occur immediately if \(t\) is larger than the lifetime \(L\). While using this model both \(n\) and \(\alpha\) can be found from two aging tests.

With \(m\) different failure causes, each with probability \(P_i\) for \(i = 1, \ldots, m\) and causing \(a_i\) percentage of all failures, the total failure probability \(P_m\) is

\[ P_m = \sum_{i=1}^{m} a_i \cdot P_i. \]  

(8)

According to the results given in [42] 80% of the transformer failures occur in the age interval 10 to 38 years. Performed regular maintenance on transformers makes it possible to avoid an extreme increase of the failure rate. The main cause for the aging of transformers seems to be wear-out problems [42].

5.3 Models which include maintenance

5.3.1 A Bayesian method and equivalent age

In the report [9] Elforsk presents an equivalent age for the transformer as:

\[ L_e = \hat{A} + \sum LK + \sum LM \]

where \(\hat{A}\) is the transformers age, \(LK\) are the stresses from lifetime consuming factors and \(LM\) are the stresses from lifetime intensifying factors. Life time consuming factors are for example short circuits in the transformer and life time intensifying factors are for example different maintenance tasks. The \(LK\):s are positive but the \(LM\):s are negative numbers. According to the report this is an example of how the lifetime can be modeled in a bayesian lifetime analysis. However no values are proposed on \(LK\) or \(LM\).

For 6 different groups, depending on manufacture, of transformers Elforsk [9] evaluated the density function of the lifetime. A Weibull function with parameters based on an expert’s assumptions of the transformer lifetime was used as priori which was updated by lifetime observations according to Bayesian theory.
5.3.2 Failure rate based on DGA results

Zhang et.al. [43] presents a model which also uses Bayesian theory, but with the purpose to derive an optimal maintenance strategy. Before they reach at the optimal maintenance strategy they have to derive the failure rate of transformer based on DGA results.

The model presented in [43] includes the probability, \( p(k) \), for an event \( k \) in the transformer and the reduction of the probability of event \( k \) due to maintenance \( m \), \( \Delta p(k, m) \). The risk reduction due to maintenance \( m \) performed at time \( t \) is \( \Delta CR(k, m, t) = \frac{\Delta p(k, m)}{p(k)} \cdot CR(k) \) where \( CR(k) \) is the risk for event \( k \). The probability reduction due to maintenance is found from \( \Delta p(k, m) = p_{\text{before}}(k) - p_{\text{after}}(k) \) where \( p_{\text{before}}(k) \) is the failure probability before maintenance and \( p_{\text{after}}(k) \) is the failure probability after maintenance.

If the number of components, that can be maintained, in the transformer is \( N \) and \( k = 1, \ldots, N \), the number of different maintenance on component \( k \) is \( L_k \) and \( m = 1, \ldots, L_k \) then \( I(k, m, t) = 1 \) if maintenance task \( m \) performed on component \( k \) begin at time \( t \) and zero otherwise [43].

Since the aim is to reduce the risk of failure as much as possible by performing maintenance the objective function is:

\[
\max \left\{ \sum_{k=1}^{N} \sum_{m=1}^{L_k} \sum_{t=1}^{T} \Delta CR(k, m, t) \cdot I(k, m, t) \right\}
\]

where \( t = 1, \ldots, T \) is the time interval under consideration. In order to find the failure probabilities needed to perform the maintenance optimization Zhang et.al. [43] estimates the failure rate of the transformer. It is assumed that the failure probability follows a Weibull distribution with known scale parameter \( \alpha \) and an unknown shape parameter \( \beta \). Moreover it is assumed that the shape parameter \( \beta \) follows a normal distribution \( \beta \sim N(\mu, \sigma^2) \), where \( \mu \) is the mean and \( \sigma \) is the variance.

The shape parameter \( \beta \) is determined with use of Bayes’ rule and DGA results. Bayes’ rule is:

\[
P(\beta|\text{DGA results}) = \frac{P(\text{DGA results}|\beta)P(\beta)}{P(\text{DGA results})}
\]

For simplicity Zhang et.al. [43] assume that the total amount of combustible gases, \( G \), also follows a normal distribution, i.e. \( G \sim N(\omega; \beta + k_i, \omega^2 \gamma^2) \), where \( i = 1, \ldots, 4 \) corresponds to different conditions, \( k_i \) is the average amount of combustible gases in condition \( i \) and \( \omega \) is known.

Then the posterior of \( \beta \) can be found by using the linearity of the normal distribution and the Bayesian rule. Zhang et. al. found that the mean and the variance of \( \beta \) are:

\[
\mu = E(\beta|G) = \frac{\sigma^2}{\sigma^2 + \gamma^2} \cdot \frac{G - k_i}{\omega} + \frac{\gamma^2 \mu}{\sigma^2 + \gamma^2}
\]

\[
\sigma = Var(\beta|G) = \frac{\sigma^2 \gamma^2}{\sigma^2 + \gamma^2}
\]
At the end of their paper Zhang et.al. [43] presents an example of their method where DGA results from a transformer over an 8-year period have been used. In the example they use $\omega = 15$, $k = 60$, $\sigma^2 = 2$ and $\gamma^2 = 20$. The shape parameter $\beta$ is found to equal 1. Since the empirical failure rate of transformers is 2% and $\beta = 1$ the scale parameter $\alpha = 50$.

5.3.3 A Markov model gives “mean time to first failure”

In [44] a model is presented, which can be used to evaluate “mean time to first failure”. A maintenance model for the transformer is simplified to a Markov chain model, in which the transformer can be in four different stages, including the stage at which the transformer has failed. The other three stages represent different transformer conditions. In this model it is assumed that the transformer successively degrades until it fails, i.e. if the transformer is at one of the two stages corresponding to the best conditions it can not fail. From stage 1, good condition, it can only reach stage 2, ok condition, and from stage 2 it can only degrades to stage 3, not so good condition, and eventually from stage 3 the transformer can reach stage 4, fail.

The transformer can also move from any stage to a stage where the condition is better, if maintenance is performed. In the paper two maintenance models are mentioned the perfect and the imperfect maintenance model. In the perfect model performed maintenance represents by a transition to the next better stage, i.e. from stage 3 to 2 or from 2 to 1. In the imperfect maintenance model it is further assumed that an inspection at stage 1 can cause a move to stage 3.

The probabilities with which the transformer moves from one stage to another are evaluated from the maintenance model for the transformer. At the first three stages inspections and tests are performed with different probabilities. The test results categories the oil condition as good, requiring reconditioning and poor or adverse. From good oil condition the transformer moves to one of the three transformer conditions directly. In the other oil conditions maintenance must be performed. The maintenance included in the model is oil filtering and oil replacement. Depending on the transformer condition and the oil condition these maintenance tasks are given different probabilities. After the maintenance the transformer is at one of the three stages with different probabilities. The actual probabilities are not given in the paper [44], but can be found from real transformer data. The inspection rate can be varied in order to receive high reliability with minimum costs.
Many of the statistical surveys made on power transformers suffer under the problem with lack of data. When the amount of data is limited the statistical results become uncertain. Different surveys also use different classifications of failures which make them hard to compare.

The lack of data is a problem in statistical analysis of transformer failures and maintenance. The limited amount of failure statistics is a consequence of two facts. First transformers have relative long lifetimes and don’t fail frequently, second during expansions of the power system transformers are replaced with larger or better suited units before they have reached their end of life. Another thing is that transformers are not equal. They have different rated powers, voltages and currents, are different loaded and are of different designs. Therefore is it not sure that two transformers are equal in statistical meaning.

In order to decide on which part maintenance shall be performed with the aim to extend the life time of the transformer it would be good to have more failure statistics. The statistics should include information about how often different components of the transformer fails and presumed causes for failures of each component. Then the part of the transformer that stands for most failures, which can be avoided by maintenance, could be found. Further research could then be performed on that component and failure cause and its maintenance.

Information about how often different transformer components fail has been found in the literature, however information about the failure causes on component level has not been found. One conclusion is that OLTC failures stand for the major part of substation transformers failures. Winding failures come on the second place. If the transformer is not equipped with OLTC the windings stand for most failures. One survey has found that the bushings stand for the major part of all transformer failures, but in that survey a comment is made on OLTC failures that only major failures are included. A natural question is then how the figures had changed if all OLTC failures had been included and why they have used different definitions of failure on different parts.

Another conclusion is that many transformer fails due to manufacture, design and incorrect maintenance, which are causes that can’t be prevented or limited by maintenance. Incorrect maintenance can be avoided by information and education of the people that perform the work. Three other big failure causes are material, over voltages and short circuits. This causes can include different types of failures were some could be prevented by maintenance. For instance material can consist of failures due to aged materials or due to material failures from the construction. The first type could be avoided by maintained but not the second. When it comes to over voltages and short circuits the transformer is constructed to withstand them up to some limit. Failures due to over voltages or short circuits in combination whit aged or deteriorated insulation could be prevented by maintenance up to some limit.

There are many different life time models in the literature, some include maintenance others don’t. It is hard to say that one model is better than the others at this moment, it depends on the available data and what the model shall be used for. Some models need a lot of calculations and or data.
As a consequence of the limited amount of data in the first group many life time models uses Bayesian theory. The Weibull function is also often used since it can describe increasing, decreasing and constant failure rates and the available data have not showed that any other distribution would be better suited.

When DGA results has been used as data to a Bayesian model a normal distribution has been assumed as priori for the shape parameter in the Weibull function as well as for the data. This has been made for simplicity rather than based on knowledge about the connection between DGA results and the probability of transformer failure.

DGA results has also been used in a model in order to evaluate the DP-value in the cellulose isolation.

A Markov model has been used to evaluate mean time to first failure. The model is based on test intervals, repair times and probabilities to go from one condition to another. These kind of data can be found from real transformers according to the writers.

Even though most authors agree that the transformers life is not the same as the insulation life many of the proposed life time models for the transformer are indeed models of the insulation life and describes how the cellulose ages with temperature.

One model combines the Arrhenius model and the inverse-power-law in order to build a model based on electrical, mechanical and thermal stresses in the transformer. The data used in this model is information about the stresses.
7  Research project problem formulation

7.1  Life time models

A next step in life time research of transformers could be to collect more relevant statistics about transformer failures. It would be good to have statistics about parts involved in failures and statistics of how different parts fail, i.e. to allot the causes in the failure trees probabilities. Then it is possible to draw conclusions about which failure mechanism is worth to investigate further. Which part is worth preventive maintenance? Which parts fail due to causes that we can avoid and which due to causes we can’t avoid? Finally a life time model of the specific part can be evaluated. This project would have the same character as the work made by Tommie Lindquist [4] within the RCAM-group at the division.

The different life time models found in the literature could be compared further to find advantages and drawbacks. Then a model could be chosen and improved or extended.

It would also be interesting to construct a new life time model based on the knowledge about the transformers construction and its different failure mechanisms. Assume that failure mechanism $i$ can be described of a stochastic variable $X_i$. Different $X_i$ probably don’t have the same distribution function and don’t necessarily belong to the same family of distribution functions. Furthermore a dependence between some failure mechanisms is possible. With good knowledge about the transformer it should be possible to construct a function of all $X_i$ that describes the transformers failure probability. Once the model has been constructed it should be possible to extend the model to include different maintenance activities, these could for instance be described by stochastic variables $Y_i$. A great work would be to investigate the distributions for every $X_i$ and $Y_i$. Before all $X_i$ and $Y_i$ are known, it is possible to include the most important variables only, or simply assume a uniform distribution for the unknown. This project is theoretic and good knowledge about the transformer and statistics is needed.

7.2  Loading guide related research problems

It could also be interesting to study if the loading guide or any life time model is used by power supply companies to for instance regulate the loads on different transformers in order to extend the life time of the transformer. If they use the loading guide or any other life time model it would also be interesting to know how and in what extent they use it. Then it would be interesting to simulate the aging of the transformer with for instance the load regulated according to temperature limits given from the loading guide and study how much the regulation extends the transformer life. This project could be performed within the division. A first step in the project could be to construct a questionnaire.

Another interesting research problem with connection to the loading guide could be to extend the given model to include the effect of water and acids in the transformer oil and cellulose i.e. to investigate the relations between ageing rate, water/acid content and temperature. This would be a project of more experimental characteristics.
7.3 The effects of maintenance

It could be interesting to investigate the effects of different maintenance tasks, for instance reclaiming of transformer oil. This kind of study has been performed by Elforsk [30],[31] however it is still interesting to investigate the effects of maintenance further. According to [45] 26 of E.On Elnät Sverige AB’s transformers in the south region had been reclaimed until the autumn 2006. For these transformers results from DGA and oil quality tests can be found in the ABB database over E.On’s transformers. One way to investigate the effect of reclaiming transformer oil could be to compare test results from tests before and after the time when the oil was reclaimed. The results should also be compared to the behavior of oil quality in non-reclaimed transformers. This project could be made at the division within the RCAM-group.

7.4 Condition control

Another interesting research problem is to study the amount of developed gases in the transformer and see if it is possible to connect the amount of gases with how serious a failure in the transformer is by using the energy needed to develop the given gas amount. To be able to do this good knowledge about the formation of different gases in the transformer is needed. To test a theory it would be good to have DGA results from some transformers on which the failure has been found and a judgment of how serious it was has been made. However a lot of research has been made in this field and a literature study would be to recommend before starting on a project. This project needs a lot of chemistry knowledge.

A description of available data is given in appendix A.
References


A Data

Most of the statistical results in section 2 are only given as results. In order to decide what to do in the future it is important to know what kind of data there is. Therefore a description of the data available for the project today follows.

One exception is Elforsk’s report [9] where the data is given in the appendix. The data consists of 217 transformers. Of these transformers 3 had reached their technical lifetime and 2 had been exchanged for other reasons. For every transformer its owner, mark power, manufacturing year, either the year when the transformer was taken out of operation or the year when the survey was ended, age and a comment about why the transformer was taken out of operation or if it is still in operation are given. In their survey the transformers were divided into different groups depending on manufacture and manufacturing year. The group index is also given for the transformers.

An excel file over all E.On Elnäit Sverige AB’s transformers is available for the project. The file consists of information about transformers. The information is name/location of the transformer, manufacturing year, retirement year and some comments about maintenance and failures. E.On Elnäit has also given us access to their database at ABB. When the database is entered a list of E.On Elnäit’s transformers can be seen. Next to the transformer name the date for the latest oil analysis and a colored oil drop can be seen. The different colors on the oil drops respond to the result of the oil analysis, good or bad condition. By choosing a transformer a list of results from the oil analysis performed on that transformer is shown. Together with the actual gas amounts and other oil analysis results a written comment from ABB can be seen. Something about the transformers condition is said and a recommendation on when to perform a new analysis or on other tests, needed to find a suspected failure is given.

Moreover E.On Elnäit Sverige AB has an archive with one file for each transformer. In these files it is possible to find information about failures and maintenance. According to Tjäder [45] the system was working before the deregulation. According to Lapworth 2006 [19] and [18] there are number of established databases on transformer failures. Most are country based and collect information about failures on for instance transformers and the specific transformer population. From the information failure rates are derived. The Double database, however, is open to all by the internet, as long as you have a “Double Service Agreement”. Double collects data about individual faults and failures without trying to derive any failure rates.