Abstract--Due to the large amount of electrical apparatus and the costs of an individual diagnosis in medium-voltage networks, a general consideration of some representative electrical components to assess the lifetime of the electrical apparatus is necessary. Under the investigation of the general ageing mechanisms of individual electrical components, a new method for the assessment of the lifetime of the electrical components is presented in this paper. This method utilises the life model, the probabilistic failure model and the enlargement law to predict the failure probability and the failure rate of the electrical components in medium-voltage networks for a future time period. Therefore, a relationship between lifetime and reliability of the electrical components is developed which supports the decision-making in deregulation of the electrical energy market later. It is demonstrated with cable and transformer data that the method is able to assess the lifetime and reliability of the electrical components with accurate and convenient data.

Index Terms--assessment, electrical component, failure probability, failure rate, lifetime, medium-voltage network, model.

I. INTRODUCTION

In an electrical power system the asset management is introduced mainly to cut the complementary costs and to supply the high quality of the electrical apparatus and networks in a more efficient way. Thus the policy, in a comprehensive economic view, is to look for a complete solution, that gives maximum profit for minimum cost, being applicable to the whole network long term (Fig. 1).

Previous decision-making policies for medium-voltage networks have been based on a traditional approach [1], [2] where the prior data of reliability, availability and maintainability of the individual electrical apparatus are collected directly from medium-voltage networks with a specific structure, thus the influences of the data on medium-voltage networks are assessed. A network may consist of several tens of thousands of assets and electrical apparatus whereas statistical data of the electrical apparatus under different operating conditions would require a lot of various diagnostics and extremely long monitoring time. The sparse and incomplete information of key assets and electrical apparatus over a long time with various operating conditions is a major hurdle in the technical asset management. With the approach, the amount of the electrical apparatus must be reduced to a manageable size and the precision for the individual apparatus must be limited in its scope. This approach does not provide enduring analytical models by which the lessons of each failure can be effectively used on a preventative basis in the future.

II. AGEING MECHANISMS OF THE ELECTRICAL COMPONENTS

The failure statistic of German utilities [5] shows that more than 80% of the failures are caused by the electrical apparatus. To meet the requirement for the modelling of a medium-voltage network, some associated apparatus can be considered...
as a total component whereas a medium-voltage network is divided into four main electrical components, i.e. overhead lines, cables, transformers and GIS (gas-insulated switchgears and metal-clad switchgears including insulator, protection and local control). Therefore some models for the assessment of the lifetime of the electrical components are required to determine the failure reliability of the electrical components and the failure risk of medium-voltage networks.

It turns out that two main kinds of failures in the electrical components lead to failures in medium-voltage networks: external failure and internal failure (table I). The external failure caused by excavator work, storm or some stochastic accidents is one main reason for failures of the electrical components. This kind of failure is almost independent on the ageing of the electrical components, thus chances of its appearance are assumed to be constant during the whole lifetime of the electrical components whereas failure rates can be derived from [5]. The internal failure is strongly correlated to the ageing of the electrical components where failure rates are not constant for the whole life time. Therefore the ageing phenomena of the electrical components are taken into account for the applied models for the assessment of the lifetime of the electrical components.

![Fig. 2. Technical asset management](image)

Investigations have shown that the ageing of materials in the electrical components is often found to contribute to internal failures, due to the presence of degradation stresses, such as electrical, thermal, mechanical and ambient (due to the associated environment) stresses [6], [7]. Thus it becomes necessary to do basic research in the material analysis (i.e. ageing tests) in order to assess the technical lives of the electrical components.

The ageing of insulating materials is estimated by an electrical breakdown occurring in the electrical components. From a statistical point of view, the probability of electrical breakdown is described by the probabilistic failure model as a consequence of the breakdown test. Along with the life model, the probabilistic failure model about possible time to failure and the related statistical variances are given in terms of probability, failure rate, reliability of the electrical components, etc.

Combined with the enlargement law for a network, such a system of models helps to predict the failure events of the electrical components and networks under various operating conditions. Thus a timely implementation of a strategy for replacement of electrical apparatus, elimination of faults and investment in networks in combination with redesign options of the network structure is a key to success for the asset management of medium-voltage networks.

An electrical power system covers several areas of the electrical components. The typical ageing processes of the electrical components are considered to be partial discharge, electrical breakdown, formation of water trees, electro- and thermochemical processes as well as mechanical stresses. In this section the ageing mechanisms and the general degradation properties of these electrical components are studied.

### A. Cables

Medium-voltage cables (XLPE, paper-insulated cable, etc.) have been extensively installed and used for many years. The mechanisms of ageing and electrical breakdown of medium-voltage cables have been investigated with computer-aided measurement systems and sophisticated methods of material analysis. Many failures in the medium-voltage cables are caused by damage due to excavation activities. But quite a few electrical breakdowns are still caused by the internal failure of cables.

For medium-voltage cables the development of water trees as a major degradation phenomenon has become well known [8]. In the presence of water the corrosion of reinforcing tapes and the change in the crystalline structure of the cable insulation are the main ageing factors. Combined with harsh environmental conditions, an excessive loading (electrical stress) may cause an increase in the loss factor of the insulating materials. In general, the character of tree growth and ageing of solid material appears to be almost Inverse-Power-Model in nature.

The ageing process of most insulation materials can speed up, when the temperature of the materials is increased. Due to overheating, the failures may occur as a result of the increased losses inside the insulating materials. The behaviour of a chemical-bond-breaking reaction can be expressed by using the Arrhenius-Model.

### B. Transformers

The ageing of transformers is related to the ageing of

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>FAILURE STATISTICS</th>
</tr>
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<tbody>
<tr>
<td>Electric Component</td>
<td>Failure Percentage</td>
</tr>
<tr>
<td>Cable</td>
<td>23 %</td>
</tr>
<tr>
<td>Overhead line</td>
<td>46 %</td>
</tr>
<tr>
<td>GIS</td>
<td>24 %</td>
</tr>
<tr>
<td>Transformer</td>
<td>7 %</td>
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windings, tanks, bushings and on-load tap changers. The ageing of windings depends strongly on the usage history of transformer, particularly on the thermal stress due to an overload. Tanks are affected by corrosion, which is related to operating time and maintenance history. The ageing of bushings by the thermal stress depends on the operating load of the transformer [6]. During the normal operation of on-load tap changers, the electrical behaviour of oil-impregnated transformers is affected by the produced particles, which correspond to the load current as well as to temperature and time.

In oil-impregnated transformers, much attention has been paid to the diagnosis of the status of the cellulose insulating material (paper and pressboard). The insulating paper around the conductors may be broken down, if it has been aged previously due to the heat dissipation of the winding or due to the presence of water. Thus, the effects of temperature and water on the life of transformers should be taken into consideration when the life model is made. Like other solid insulation materials, the life characteristics of insulating paper and oil-impregnated transformers can be well described by the Inverse-Power-Model and Arrhenius-Model.

C. GIS

GIS has shown high reliability for more than 20 years. The high reliability is attributed to the encapsulation of the electrical components and the use of excellent insulators made of epoxy resin and of insulating gases (air or SF6).

For the development of the life model we review ageing mechanisms of insulating gas and solid insulators in GIS. Conducting particles attached to the surface of insulators may generate partial discharges if they are located in a position under a high electrical stress [9], [10]. If the electrical stress continues for a long time, the decomposition products caused by the partial discharges degrade the surface of the insulator and lead to the generation of tracks. When conducting particles are present in GIS, the dielectric strength of the insulating gas tends to decrease with time if a voltage is applied. This is called the voltage-time characteristic which satisfies the empirical Inverse-Power-Model.

The main problem of the ageing of protection and control systems with electro-mechanical solid-state components results from deteriorating properties as they approach at the end of their lives. For the micro-electronic components, thermal stress is expected to be a key factor in the ageing of protection- and control system [11].

D. Overhead Lines

Corrosion is the most adverse ageing consequence of overhead lines. The amount of corrosion depends mainly on environmental conditions: ambient temperature, precipitation, pollution and mechanical forces due to wind or ice and time [5], which are described as well by the Inverse-Power-Model and Arrhenius-Model.

Of course, some stochastic accidents are the main reasons of failure for overhead lines, thus chances of their appearance are assumed to be constant.

III. LIFE MODEL

The determination of the electrical, thermal and mechanical degradation of the electrical components in this study is limited to the establishment of an empirical correlation. This, along with a minimum of adjustable parameters, can successfully predict the degree of degradation of the electrical components under the influences of electrical, thermal and mechanical stresses.

A chance for the development of a electro-thermal life model is given by the phenomenological theory of ageing [12], [13]. If a generic combination of electrical and thermal stresses is applied to an electrical component, a suitable life function $t$ of the electrical component can be established according to the following relationship:

$$t = t_0 \left( \frac{E}{E_0} \right)^{-n} \cdot e^{-BT}, \quad T = 1/\theta_0 - 1/\theta$$

where $n$ is the voltage endurance coefficient, $E_0$ the lower limit of the electrical stress (below which the electrical ageing can be neglected), $B$ proportional to the activation energy of the main thermal degradation reaction, $T$ the conventional thermal stress, $\theta$ the absolute temperature, $\theta_0$ a reference temperature, and $t_0$ the corresponding life at the temperature $\theta_0$ and the electrical stress $E_0$.

The proposed electro-thermo life model comes from a suitable combination of two single-stress models, i.e. an electrical life model and a thermal life model, which can be represented by the Inverse-Power-Model and the Arrhenius-Model, respectively. This can be done by simply assuming, that the ageing rate under two combined stresses is the product of the ageing rates under each single stress. If a mechanical stress is considered, the mechanical life model is equivalent to the electrical one, that can be expressed, i.e. by the Inverse-Power-Model.

Under the influence of a thermal stress on the electrical breakdown the combined electro-thermo life model will result in an overestimation of the synergism between stresses, which leads to an underestimate of life especially at high stresses. Therefore, it seems reasonable to introduce a suitable corrective function $(E/E_0)^{-B}T$ in order to consider the influence between stresses and to achieve a better fit of the experimental data. In this case, the following expression has been assumed for $t$:

$$t = t_0 \left( \frac{E}{E_0} \right)^{-B} e^{-BT}$$

It is a more reliable approach to determine the parameters $n$ of (2) directly by ageing tests for the individual electrical components. The long term ageing test or the accelerated ageing test with an increased voltage is quite often used for assessing the lifetime of the electrical components.

IV. PROBABILISTIC FAILURE MODEL

When an electrical breakdown occurs in insulating
materials under an electrical stress, the failure has to be specified by the so-called electrical withstand strength which is assigned to the event “non-breakdown” at the highest electrical field strength but derived from the event “electrical breakdown”. Therefore, an accepted statistical model of determining the likelihood of failure at the given stresses is compared with the shape of an exponential function. It is recognisable, that such an empirical function can be well described by the Weibull-function [14]. The two-parameter Weibull-function can be written as:

$$p(E) = 1 - \exp \left[ - \left( \frac{E}{E_{63\%}} \right)^\beta \right]$$

(3)

where \( p \) is the function of failure probability of an electrical component, \( \beta \) the shape parameter, which can be obtained by breakdown tests, and \( E_{63\%} \) the electrical withstand strength of the Weibull-function, whereas the according failure probability is 63%.

An electrical breakdown would occur if an over-voltage is applied or if an electrical component is aged by temperature or time. Therefore a criterion for the electrical breakdown is consistent with the electrical and thermal lives. With an estimation of the electrical withstand strength \( E_{63\%} \), (2) is applied in (3) to determine the failure probability of an electrical component under the influences of electrical and thermal stresses:

$$p(E, T, t) = 1 - \exp \left[ - \left( \frac{E}{E_0} \right)^\beta \cdot \left( \frac{t}{t_0} \right)^{\frac{\beta}{n+bT}} \cdot e^{\frac{\beta BT}{n+bT}} \right]$$

(4)

As a multi-stress model the Weibull-function (4) provides a probabilistic failure model giving the failure percentiles for each pair of stresses.

V. ENLARGEMENT LAW

An electrical power system consists of several tens of thousands of assets and a large number of electrical components. The basic problem is, that in laboratories or test plants only an individual electrical component (e.g. a cable with length and diameter) with a short test duration (e.g. the accelerated ageing tests) is investigated. For practical applications it is desirable to describe the properties of all electrical components and to predict an extending lifetime of the entire system in service.

From a statistical point of view, all these questions can be dealt with by using the enlargement law [15], which represents the statistical model of the multiplication law for non-dependent probabilities. The non-dependence of the failures, which take place in parallel with respect to space (volume-effect) and time (time-effect), is of course assumed.

The total probability \( P \) of the non-dependent failures with the non-dependent events \( m \) can be derived from

$$P(E, T, t) = 1 - \prod_{i=1}^{m} [1 - p_i(E, T, t)]$$

(5)

If an element component with volume \( V_i \) and time \( t_i \) has a failure probability \( p_i \), the total probability \( P \) of the entire electrical component with volume \( V \) and time \( t \) is calculated by the integral of (6):

$$P(E, T, t) = 1 - \exp \left[ \frac{1}{V_i t_i} \sum_{i} V_i \ln(1 - p_i(E, T, t)) \right]$$

(6)

VI. APPLICATION OF THE MODELS

For instance, the voltage endurance coefficient \( n \) of (2) results from an ageing test if two lifetimes \( t_1 \) and \( t_2 \) of an electrical component at the ambient temperature are plotted versus the electrical field strengths \( E_1 \) and \( E_2 \), respectively:

$$n = \frac{\log t_1 - \log t_2}{\log E_2 - \log E_1}$$

(7)

In a similar manner, if two probabilities \( p_1 \) and \( p_2 \) from the breakdown test at the ambient temperature are plotted versus the field strengths \( E_1 \) and \( E_2 \), respectively, the shape-parameter \( \beta \) of (3) can be obtained as:

$$\beta = \frac{\log[1 + (1 - p_1)/(1 - p_2)]}{\log E_1 - \log E_2}$$

(8)

On the basis of the known parameters \( n \) and \( \beta \), the thermal coefficients \( b \) and \( B \) of (2) can be obtained by ageing tests at two different temperatures. This can be realised by application of an electrical stress, able to give rise to breakdown when the electrical component is aged by temperature.

The models characterised by four parameters, i.e., \( n, b, B \) and \( \beta \) provide the lifetime of an electrical component shown in Fig. 3. In the case of the combined electrot-thermal stresses, the three-dimensional lifetime can provide the electrical life lines at \( T = 0 \) or the thermal life lines at \( E \cdot E_0 = 0 \) that follow the Inverse-Power-Model or the Arrhenius-Model.

It is known from the statistical theory of failure, that the density of failure probability \( f(t) \) and the failure rate \( h(t) \) are determined by the function of failure probability \( P(t) \):

$$f(t) = \frac{d P(t)}{dt}$$

(9)

$$h(t) = \frac{1}{1 - P(t)} \cdot \frac{d P(t)}{dt}$$

(10)

According to (9) and (10) the density of failure probability and failure rate of an electrical component are considered as a function of time.
Fig. 4 shows the calculated and statistical failure rates of one type of a XLPE-insulated medium-voltage cable derived from the special VDEW-statistics [16] for the manufacturing year 1975. For a calculation, the characterised parameters of (4) have been determined on a sample of a model cable. By the enlargement law of (6) the failure rate and the failure probability for the cable of 1 km can be calculated.

It can be seen in Fig. 4 that the failure rate rises over the years according to the increasing right wing of the well-known bathtub curve. In the case of an earth fault the reason of failure is usually the water tree correlating strongly to the age of the cable. During the first years of a cables’ lifetime the failure rate is constantly low. But after about 8 years of operation the ageing phenomenon causes a steep increase of failure rate of cable at the end of life, thus indicating an impending failure and showing the strong influence of the age on failure.

Typically the available data of failure rate in Fig. 5 for a transformer is derived from a limited population [17] and is a discrete rather than a continuous curve. However it is appropriate to derive a theoretical distribution of failure rate for the prediction of lifetime if these models are applied to the transformer under examination. This is in fact the increasing failure rate relating to the most likely life of the transformer. It is possible to attempt residual life estimations from a failure rate.

For the comparison of failure rates and densities of failure probability at different parameters \( n \) and \( \beta \) the calculated results for the cable and the transformer are shown in Fig. 6 and Fig. 7. In Fig. 6 it is very obvious that the failure rate of the transformer with \( n \) of 6.5, \( \beta \) of 5.0 and \( \beta/(n-bT) \) of 3.3 is lower than the failure rate of the cable with \( n \) of 8, \( \beta \) of 12 and \( \beta/(n-bT) \) of 3.8. The transformer with the larger voltage endurance coefficient \( n \) as well as the smaller shape parameter \( \beta \) and the smaller \( \beta/(n-bT) \) has a better dielectric strength and a longer life than the cable. In fact, such a situation arises, when electrical and thermal stresses and time are applied at the same time.

When calculating the density of failure probability, this can be approximated to a normal distribution with an average expected lifetime of 15 and 45 years for the cable and the transformer, respectively. The peak value of density of failure probability for the transformer is lower than the one for the cable and declines with time. Multi-event and overall substation reliabilities can be easily derived from such figures using simple probability theorems.

Now the influences of the electrical and thermal stresses on the failure rate and the on density of failure probability can be investigated. With declining electrical field strength (small \( \beta \))
VII. CONCLUSION

An advantageous method of technical asset management for the electrical components has been developed for the purpose of assessing the reliability of electrical power systems.

Typical ageing processes of the electrical components are considered to be due to electrical, thermal and mechanical processes. Therefore the ageing processes are transferred into a life model, which is presented by the Inverse-Power-Model and the Arrhenius-Model. In reliability calculations of medium-voltage networks the multi-models from the life model, the probabilistic failure model and the enlargement law are applied to provide effective predictions for the failure probability and the failure rate of an electrical component and a network.

Due to the ageing phenomenon the increasing failure rates of one type of the XLPE-insulated medium-voltage cable and the power transformer, for example, can be calculated and demonstrated as well by the data from the VDEW statistics and [17]. The assessment of the reliability results of a transformer and a cable can be viewed as objective evidence that the reliability requirements of an electrical component will be satisfied by the proposed technical parameters and operating conditions.

In this way there is the prospect of being able to estimate the electrical power systems for working conditions with accurate and convenient data.

VIII. REFERENCES


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