Estimation of the Failure Rate of the Electrical Components with Respect to the Dimension of Medium-Voltage Networks

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Abstract — This paper represents a first attempt at modeling lifetime reliability for representative electrical components due to electrical stress, mechanical stress and temperature, taking general aging mechanisms of insulating materials into consideration. Thus the proposed models provide reliability estimates, i.e. the failure rate for medium-voltage networks. These models can be parameterized through aging tests as well as with a great deal of statistical data being available for the probabilistic assessment. The results imply that the assessment approach for the component reliability will motivate a need for reasonable and accurate data at an early decision-making stage in future deregulation of the electric energy market.

Index Terms — Component reliability, Electrical component, Lifetime, Failure rate.

I. INTRODUCTION

It is often taken for granted that the lifetime of installed electrical equipment is less than 40 years. At reaching the moderate age of electrical equipment, the reinvestment of maintenance and replacement has to be considered. The life span of 40 years for electrical equipment means that an annual ratio of the total reinvestment amounts to 2.5%. However, in many enterprises, the annual expenditures for maintenance and replacement average only 1%, which corresponds to an expected lifetime of 100 years of electrical equipment. Due to the limited reinvestments, the age of electrical equipment will increase. It is indisputable that the age of electrical equipment endangers the safety and the reliability of power supply.

Extensive basic research work has detected the aging phenomena and aging processes of typical insulating materials under test or working conditions. However, most of these studies have been performed at the experimental level, only considering individual failure mechanisms of insulating materials. Additionally, they are performed in the fixed case without any knowledge of the target application. Thus, the incomplete analysis of experiment would produce unrepresentative data of aging behavior for the electrical equipment in medium-voltage networks.

Based on the quantitative evaluation of historical failure data from the medium-voltage networks [1] and [2], this paper analyzes the aging mechanisms of the typical electrical components and develops a reliability model of component by coupling the life model with the probabilistic failure model. Therefore, the work should focus not only on reflecting and responding to the way electrical equipment fail but also on deducing the failure consequences by connecting statistical data to durable evaluation models. Once the future failure distributions are introduced through different equipment types, service conditions and network structures, the achieved results will contribute to a model of component reliability based on the evaluation of failure statistic.

II. AGING MECHANISMS OF THE ELECTRICAL COMPONENTS

Investigations have shown that the aging of materials in electrical components is often found to contribute to failures, due to the presence of degradation stresses such as electrical, thermal, mechanical and ambient (due to the associated environment) stresses [2]. Thus it becomes necessary to analyze the aging mechanisms of materials and to conclude the general degradation properties of electrical components.

Cable system. For medium-voltage polymer cables, the development of water trees as a major degradation phenomenon has become well-known, and extensive research has been performed on modeling and understanding its effects. In the presence of water, the corrosion of reinforcing tapes and the change in the crystalline structure of cables are the dominant aging factors. Combined with harsh environmental conditions, an excessive loading (electrical stress) may cause an increase in the dissipation factor of insulating materials.

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

$$L \propto e^{-\frac{T}{T_0}}$$  \tag{1}

where $n$ is the electrical endurance coefficients, $L$ and $E$ are the lifetime and the electrical stress, respectively.

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$$L \propto e^{-\beta T}, \quad \frac{1}{T} = \frac{1}{T_0} - \frac{1}{T}$$  \tag{2}
where $B$ is proportional to the activation energy of the main thermal degradation reaction, $T$ is the conventional thermal stress, $\theta$ is the absolute temperature and $\theta_0$ is a reference temperature.

**Secondary substation.** In oil-impregnated transformers, much attention has been paid to the condition diagnosis of the cellulose insulating materials (paper and pressboard). The insulating paper around the conductors decays if it has been previously aged due to the heat dissipation of windings, the loss induced by eddy-current or the presence of water. In order to consider the interactions between the electrical and thermal stresses, a suitable corrective function is introduced as following

$$L \propto E^{-\beta T}$$  \hspace{1cm} (3)

where $b$ is a correct coefficient taking into account the reaction of the material due to combined stress application.

For the development of the life model, a review of the aging mechanisms of insulating materials used in onload tap changers and load-interrupters was done. On-load tap changers and load-interrupters are aged by the charge particles produced in the insulating oil or the insulating gas corresponding to the load energy. If the electrical stress continues for a long time, the partial discharges produce more decompositions so that the dielectric strength of insulating materials tends to wear down with time, and fails when a conductive path is formed in the dielectric medium. This is named the voltage-time characteristic of insulating materials which satisfies the empirical Inverse Power Model.

**Switchgear station.** This is a phenomenon whereas circuit-breakers are typically aged due to wear-out processes such as material fatigue under cyclic load. Due to normal vibration or frequent operation, the leakage of oil is most pronounce in hydraulic drive. Permanent damage accumulates every time there is a cycling fatigue in drives, eventually leading to failure. The fatigue crack propagation approach, similar to the electrical life model, may model cycling fatigue in mechanical strength. A mechanical failure is considered to have occurred when the formed void grows above the threshold length. Hence, mean time to failure is proportional to the threshold length, and inversely proportional to the mechanical stress acting on electrical components, thus

$$L \propto M^{-m}$$  \hspace{1cm} (4)

where $m$ and $M$ are mechanical endurance coefficient and mechanical stress respectively.

**Overhead line.** Corrosion is the most adverse aging consequence of conductors in overhead line. The amount of corrosion depends mainly on the environmental conditions: ambient temperature, precipitation, pollution and mechanical forces due to wind or ice and time. The another failure reason for conductors are stochastic accidents such as storm, snow and lightning. All these terms result in a decrease in lifetime with mechanical, electrical and thermal influences that is also described by the Inverse Power Model and the Arrhenius Model.

### III. Probabilistic Failure Model

Statistical treatment of aging test data is a fundamental topic in evaluating material endurance to single or multiple stresses. Regarding the aging of insulating materials subjected to combined electrical, mechanical and thermal stresses, the Weibull function is generally used to treat failure time obtained from aging tests. Therefore, an accepted statistical model of determining the likelihood of failure $P$ at given stresses is compared with a shape parameter $\alpha$ and can be well described by

$$P(L) = 1 - \exp \left( -\left( \frac{L}{L_{63\%}} \right)^{\alpha} \right)$$  \hspace{1cm} (5)

where $L_{63\%}$ is the failure time for the failure probability of 63\% as a function of the lifetime $L$, at which a fraction (1- $e^{-1}$) equal to 63\% of the electrical components has failed. The component quality is described by the scale-parameter $\alpha$ where the responsiveness to stress application can be acted for $\alpha$.

In this way the equation (5) becomes the probabilistic failure model for the combined stresses. That is, a functional relationship between the failure distribution and the applied stresses, provides life lines at different probabilities. It shows that temperature has an exponential detrimental impact on failure probability - more than exponential results from temperature itself and less than exponential results from electric field strength. A positive effect of temperature on failure probability is observed due to the electrical threshold at the elevated temperature. In this case, the electrical stress is not an aging factor but simply becomes the last cause of failure in a material extremely aged by temperature. The failure probability is all detrimentally impacted by electrical stress, mechanical stress, and adversely affected by increasing lifetime at once.

The Weibull function for the probabilistic failure model correlates well with the stochastic accidents. The environmental influences also have an exponential impact on the failure probability, thus chances of their appearance are assumed to be constant. The only difference in the probabilistic failure model arises from the choice of $\alpha$ value.

For electrical components, the failure rate is the most important criteria besides the failure time. The failure rate allows the electrical components in different asset classes to be compared with each other and to make reference to several criteria like age, number of operation, time between events etc. In addition, all reliability issues, i.e. technical and economic estimations are dependent on the failure rate and vary with it.
IV. RESULTS AND DISCUSSION

It is a more reliable approach to determine the parameters \( n \) and \( m \) of (1) and (4) directly through aging tests. On the basis of the known parameter \( n \), the thermal coefficients \( b \) and \( B \) of (2) and (3) can be obtained by aging tests at two different temperatures. This can be realized by the application of an electrical stress which leads to failure if the electrical component is aged by temperature. According to aging tests, one part of parameters of (1) - (4) can be accepted as shown in Table 1. In most cases, no change of these parameters is to be expected under service conditions as long as the material properties do not significantly change.

### Table I

<table>
<thead>
<tr>
<th>( n )</th>
<th>( m )</th>
<th>( b ) (K)</th>
<th>( B ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td>2.3</td>
<td>6000</td>
<td>17000</td>
</tr>
</tbody>
</table>

In the following the application of the proposed models is demonstrated through an example. For this purpose, a specific failure statistic [1] from the historical failure events is especially evaluated. By that other parameters of (1), (2), (4) and (5) can be optimized as reported in Table II. These parameters are carefully chosen to match up with the statistic data, while also satisfying the calculation models. For most components these models as well as suitable parameterisation can be applied. Even in some cases where the actual data is derived from practical operation, the models for a component type are available.

### Table II

<table>
<thead>
<tr>
<th>Component</th>
<th>( \alpha )</th>
<th>( E )</th>
<th>( M )</th>
<th>( \delta ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>8.1</td>
<td>13</td>
<td>( 5\times10^{-4} )</td>
<td>25</td>
</tr>
<tr>
<td>Enclosure</td>
<td>9.3</td>
<td>5</td>
<td>( 5\times10^{-4} )</td>
<td>25</td>
</tr>
<tr>
<td>Disconnector</td>
<td>7.1</td>
<td>5</td>
<td>( 5\times10^{-4} )</td>
<td>25</td>
</tr>
<tr>
<td>T-transformer</td>
<td>11.6</td>
<td>11</td>
<td>( 16\times10^{-4} )</td>
<td>40</td>
</tr>
<tr>
<td>D-transformer</td>
<td>9.9</td>
<td>10</td>
<td>( 18\times10^{-4} )</td>
<td>40</td>
</tr>
<tr>
<td>Interrupter</td>
<td>13.3</td>
<td>10.5</td>
<td>( 17\times10^{-4} )</td>
<td>40</td>
</tr>
<tr>
<td>Circuit-breaker</td>
<td>8.3</td>
<td>10</td>
<td>( 17\times10^{-4} )</td>
<td>40</td>
</tr>
<tr>
<td>Paper-cable</td>
<td>8.2</td>
<td>6.5</td>
<td>( 2.4\times10^{-4} )</td>
<td>60</td>
</tr>
<tr>
<td>VPE-cable</td>
<td>6.6</td>
<td>7.5</td>
<td>( 2.4\times10^{-4} )</td>
<td>60</td>
</tr>
</tbody>
</table>

D-transformer: distribution transformer; T-transformer: transmission transformer. The threshold value of the electrical strength or mechanical strength is 5 kV/mm or \( 2.4\times10^{-4} \) N/mm².

In particular, the random failure for conductors, cables and transformers is caused by some external effects, e.g. storm, excavator work or regular operating fault. This kind of failure is almost independent on the aging of electrical components, thus the probabilities of their appearance are assumed to be constant. In this case, the parameters of (1), (2), (4) and (5) are optimize at \( \alpha=1 \) and shown in Tables II and III. By that the Weibull function (5) can be oversimplified into an exponential function.

### Table III

<table>
<thead>
<tr>
<th>( M ) (×10⁷ N/mm²) of (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>70</td>
</tr>
</tbody>
</table>
1-enclosure; 2-D-transformer; 3-conductor; 4-T-transformer; 5-paper-insulated cable; 6-VPE-cable.

If we consider the structural quantity of the local networks, the dimension of all considered medium-voltage networks should be given in Table IV.

### Table IV

<table>
<thead>
<tr>
<th>Quantity Structure of the Considered Networks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
</tr>
<tr>
<td>1 (km)</td>
</tr>
<tr>
<td>3700</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>1819</td>
</tr>
<tr>
<td>1-overhead line; 2-paper-cable; 3-VPE-cable; 4-enclosure; 5-D-transformer; 6-T-transformer; 7-load-interrupter; 8-circuit-breaker; 9-disconnector.</td>
</tr>
</tbody>
</table>

Combining the operating conditions and the typical parameters given in Tables I, II, III and IV the calculated failure rates of the different components in overhead lines, cable systems, substations and switchgear stations are shown in Figures 1 to 9, respectively.

The mean time to failure is directly proportional to the failure rate. From Figures 1 to 9 the expected average lifetimes of the electrical components can be estimated to be about 33 years for conductors and enclosures, 30 years for circuit-breakers, transmission transformers and load-interrupters, 28 years for distribution transformers, paper-insulated cables and disconnectors, 22 years for VPE-cables, respectively. This is in line with the findings based on considerations of the critical physical phenomena and investigations of the statistical long-term performance.

![Fig. 1. Calculated failure rate of conductor in overhead line.](attachment:image1.png)
Fig. 2. Calculated failure rate of paper-insulated cable in cable system.

Fig. 3. Calculated failure rate of VPE-cable in cable system.

Fig. 4. Calculated failure rate of enclosure in substation.

Fig. 5. Calculated failure rate of distribution transformer in substation.

Fig. 6. Calculated failure rate of load-interrupter in substation.

Fig. 7. Calculated failure rate of circuit-breaker in switchgear station.

Fig. 8. Calculated failure rate of transmission transformer in switchgear station.

Fig. 9. Calculated failure rate of disconnector in switchgear station.
In accordance with a typical wear-out failure mechanism, circuit-breakers and disconnectors have an extremely low failure rate at the beginning of the component’s lifetime. However, circuit-breakers, for example, suffer not only from the leakage of oil and the frequent operation but also from the deterioration of insulating materials and the electrical fault of protection and control systems, their failure rates will grow as the component ages up to 20 years. The curve shows a rising characteristic so that a distinct dependence on age is observable. After a first peak, the increase in failure rate is brought down to 0.00125 failures/year from 0.00275 failures/year by way of intensive repair and part replacement for the considered circuit-breakers. At ages higher than 40 years, circuit-breakers can potentially not operate reliably as extending the lifetime leads to another rise in failure rate.

It is well-known that VPE-cables of the old generation due to water tree are affected by rapid ageing. This reflects on the high failure rate of VPE-cables, originating mainly from the 1970 to 1980 years, which are clearly worse than other types of cable like paper-insulated cables. As expected the VPE cables feature the worst value at 0.005 failures/year, a fifth of which amounts to the failure rate of paper-insulated cables. The results can be explained that water tree and excavation activities damage the electrical and mechanical strengths of the cable sheath.

Figures 4, 5, 6 and 8 exhibit the characteristics for enclosures, distribution transformers, load-interrupters and transmission transformers which have an obvious dependence on age. After a certain time, the influence of maintenance can be clearly seen that the failure rate increases until maintenance activities take place and then it falls back again to a lower value. In order to decrease the failure rate and the resulting impact on reliability, corrective maintenance should be taken. The failure behaviors of conductors and paper-insulated cables differ from the increasing failure rate. As shown in Figures 1 and 2, paper-insulated cables and conductors have more dependence on random failures that the failure rates are evenly distributed over the total operating time. The average failure rates of conductors, transmission transformers, enclosures, distribution transformers, and load-interrupters are 0.0025, 0.0027, 0.00005, 0.0003 and 0.00007 failures/year, respectively.

To investigate the influences of stresses on the failure rate, the three types of electrical equipment, i.e. VPE-cable, circuit-breaker and disconnector were chosen with the worst-case values, and examine their characteristic parameters. As can be seen from Table II, the characteristic parameters for application correlate well with temperature. At each temperature, these electrical equipment are affected by different failure mechanisms. The application of electrical stress will lead to failure if the electrical component is aged by temperature. Therefore, the applied temperature may be divided into 60°C, 40°C or 25°C respectively considering that there is only an electrical impact, a combined interaction between electrical and thermal stresses, or a simply mechanical stress on an electrical component.

At ϑ=60°C, VPE-cable with \( E=7.5 \text{ kV/mm} \), due to high electrical stress, has an increasing failure rate. Although circuit-breakers have the best component quality (\( \alpha=8.3 \)), lower electrical and mechanical stresses (\( E=10 \text{ kV/mm}; M=17\times10^{-4} \text{ N/mm}^2 \)) than distribution transformers, an extreme increase of the failure rate for transformers can be avoided due to regular maintenance. For disconnectors, the stress dependence is underscored by the difference in mechanical stress where the only distinction is from the parameter \( M=58\times10^{-4} \text{ N/mm}^2 \).

V. CONCLUSION

Based on the ageing mechanisms of insulating materials, this paper models the component reliability and calculates the failure rates of typical electrical components with the respect to the quantity structure of the medium-voltage networks.

Typical aging processes of electrical components are considered to be due to electrical, thermal and mechanical processes. Therefore the aging processes are transferred into a life model, which is represented by the Inverse Power Model and the Arrhenius Model. In reliability calculations, the multi-model from the life model and the probabilistic model is applied to provide effective predictions for the lifetime, the failure probability and the failure rate of electrical components.

The increasing failure rate of circuit-breakers, VPE-cables and disconnectors due to the aging phenomenon can be calculated. This proves that all future failures are stimulated and the decrease of reliability is very sharp. With declining stress and low temperature the failure rates are lower for enclosures and paper-insulated cables. From failure behaviors of overhead lines and cables it can be concluded that failures are mainly caused by stochastic events, whose failure rates are constant.

REFERENCES

