Application of Statistical Methods for Making Maintenance Decisions within Power Utilities

Key Words: statistics,reliability, insulation life, cable joints, epoxy-resin bushings

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Statistical methods can be applied to support important maintenance decisions, using both the data obtained from diagnostic measurements and life data.

Introduction

The practical interest of power utilities regarding the maintenance policy of insulating systems such as cables, switchgear, and transformers in each case leads to the fundamental question about repair or replacement.

Without doubt, for the support in drawing such conclusions, one leans on knowledge from past experiences. The most powerful tools now seem to be:

- Diagnostic measurements performed on the components in the field [1], [2];
- Analysis of lifetime data obtained for the components under discussion.

In both cases some important problems arise, connected to the application of statistics and its mathematical analysis [3]–[6].

In this article, the theoretical considerations that have to be taken into account when using statistical failure analyses of service-aged components are discussed. Furthermore, two case studies in which statistical failure analysis is used to predict future failures and to see in what way strategies can influence this prediction are included. Then, conclusions are drawn based on the analysis of the two case studies.

Theoretical Background

In order to be able to use statistical analysis, the proper data need to be collected, i.e., the data should have the following properties:

- randomness,
- independency,
- homogeneity,
- sufficient amount of data.

Lifetime data are gathered during the whole life of given technical components, starting with the installation. This is explained best by referring to the so-called bathtub curve, Figure 1(a). The curve describes the development of the number of failures per unit of time, the failure rate $\lambda(t)$, according to the age of the component. This bathtub curve describes the failure rate of the power components discussed in the case studies. The shape of the failure rate curve in region I is characterized by a decrease, indicating failures in early life. The so called useful life (II), in the restricted time region, shows a constant failure

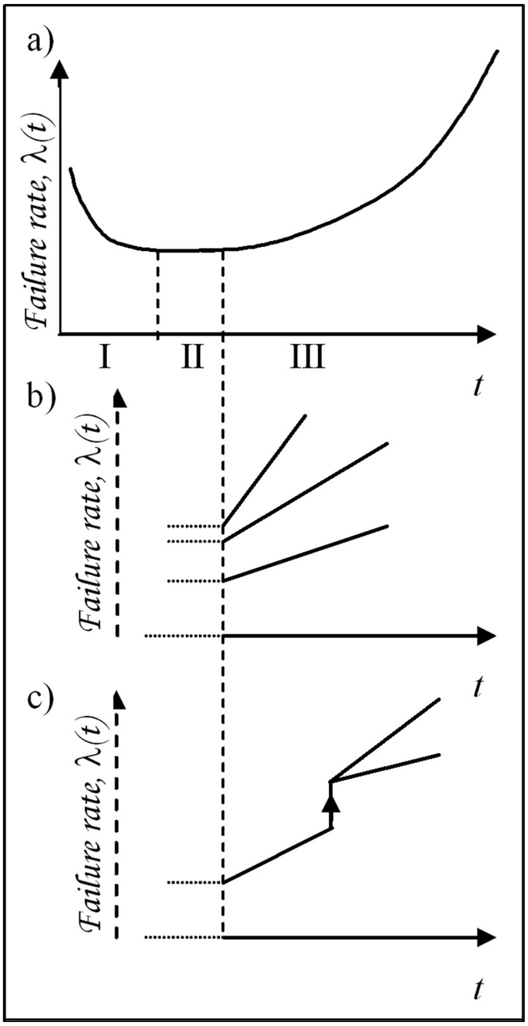

Figure 1. Bathtub curves and specific aspects important for the service life maintenance of HV components. (a) Typical phases during the service life. (b) and (c) Different possibilities of obtaining failure rates.

rate, indicating random failure behavior. The practical and useful life until the end of operation (III), stretched for over 15 to 50 years of service, is connected with the presence of different wear-out and aging processes.

Looking at the bathtub curve, we ought to mention the possibility of several levels and rates-of-rise for the failure rates, as shown in Figure 1(b). Depending on the degree of aging the slope of the failure-rate curve can be large or small. The failure rate may show a continuously increasing trend, but discontinuities also may be observed following different maintenance actions and/or changes in the environmental conditions. This means that the failure rate curve can change in time, Figure 1(c).

Some statistical methods/tests can be used to check the independency of the gathered data. Both the independency and homogeneity of data are associated with the physical and chemical properties of the components under consideration. Studying the influences and constraints connected with the given random events offers the possibility of a better understanding of the nature of failures under discussion. Furthermore, it allows the application of formalized statistical procedures to obtain conclusions in a proper way [7].

Application of Statistical Methods for Life Data and Breakdown Analysis

Dispersion of data is often present when, for instance, failure data of high voltage (HV) components are considered. These failure data can be evaluated statistically by using either the so called statistical parametric methods, or the nonparametric (ranged/sturdy) methods [8]. In this paper, the parametric method is used, in which statistical distributions are used to fit the data and to estimate the accompanying parameters.

The chosen distributions (probability models) are used to explain the behavior of the breakdown processes or the life data. These processes are described as random events resulting in random variables that can have a discrete or continuous character [9]–[11]. Life data, reliability parameters, and, in fact, the results of the majority of measurements, are examples of continuous variables. Examples of discrete random variables are the number of faults/breakdowns following the application of a voltage of given shape and duration. For the statistical evaluation of data obtained on HV components, the most popular models/distributions are:

- in the case of discrete random variables: binomial or Poisson distributions,
- in the case of continuous random variables: normal/log-normal, exponential, Weibull, and Gumbel distributions.

A straightforward procedure to obtain proper conclusions about populations of dispersed data is the following (see Figure 2):

- Use a way of sampling that ensures the randomness and independency of a sufficient number of gathered data. In this respect, the method of design of experiments is worth cosideration. This is especially the case when a new design of a component is tested, and the results are compared with a previous design.
- Apply the methods of descriptive statistics to get a first impression of the failure behavior. To do this, one can think of the frequency presentation like histograms and polygons and cumulative frequencies of occurrence.
- Perform analyses with different statistical distribution models. With different available goodness-of-fit tests (like the correlation coefficient, Pearson, Kolmogorov-Smirnov, etc.), the best fitted distribution can be determined. As a next step, the parameter(s) of a distribution under discussion can be estimated. Practical examples concerning these topics are presented in the case studies in the following section.

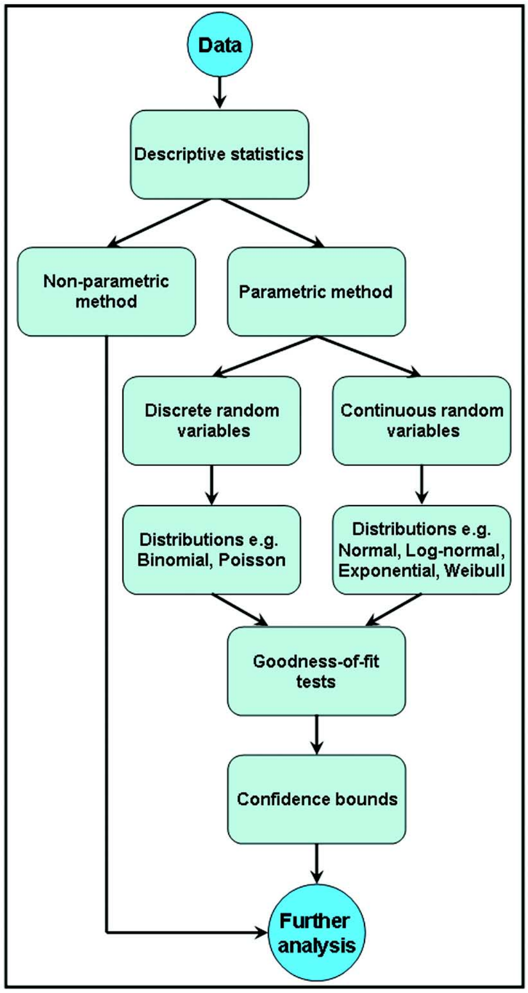

Figure 2. Evaluation flowchart of failure data.

- Point/interval estimation of parameters and/or regression functions, regarding also the benefits of confidence bounds. The amount of available data determines the statistical precision of the performed analysis. The statistical precision of the fitted distribution is shown by the confidence bounds, which indicate the repeatability of the parameter estimates in many sampling trials.
- Compare groups of test results, using the analysis of variance (ANOVA) methodology. This can be used to compare the results of two or more different groups and to determine in what way these differ from each other.
- Of prime importance in the discussed field of application of statistical methods is the modeling of life data, especially in the case of the failure-rate function. This topic will be discussed in the case study regarding cable joints, e.g., the choice of a bad fitting distribution can have a large influence on the failure-rate function resulting in a too optimistic or pessimistic failure prediction.

Life data analysis always results in an estimate. The true value for the failure probability, the reliability, and the distribution parameters is never exactly known. But with statistical analysis, an estimate of the true values can be found with a certain amount of accuracy. The basic distributions are the cumulative distribution function (CDF) and the probability density function (PDF) and give a complete description of the probability distribution of a random variable.

If X is defined as a continuous random variable, then the probability that X takes on a value in the interval $[a,b]$ in the area under the probability density function is defined by:

$$P(a \leq X \geq b) = \int_a^b f(x)\,dx \quad \text{with } f(x) \geq 0 \tag{1}$$

The cumulative distribution function gives the probability that X will be at most a certain value x and is defined by:

$$F(x) = P(X \leq x) = \int_0^x f(s)\,ds \tag{2}$$

The reliability function can be obtained from the CDF or unreliability function and is the probability of success, or not failing, of a component before a certain time. With the failure-rate function, the number of failures per unit of time can be determined. The reliability function, $R(t)$, and failure rate function, $\lambda(t)$, are obtained by:

$$R(t) = 1 - F(t), \quad \lambda(t) = \frac{f(t)}{R(t)} \tag{3}$$

Case Studies

In this article, two case studies are presented based on actual failure data of in-service failed components. The failure data of two types of components are considered, see Figure 3.

The first set of data stems from a large population of medium-voltage resin cable joints with a relatively large number of failures [12]. Only the failures of the last 5 years are known.

The second set of data comes from a large population of epoxy-resin bushings used in 50 kV, oil-filled switchgear assemblies produced by COQ. In this case, the number of failures is small and all failures are known.

The analysis is divided in three main aspects, as shown in Figure 4:

- collection of failure data,
- statistical analysis,
- prediction of future failures.

The failure data, as well as the population still in service, are used as input for the statistical analysis. The data are fitted with an appropriate distribution, and estimates of the statistical pa-

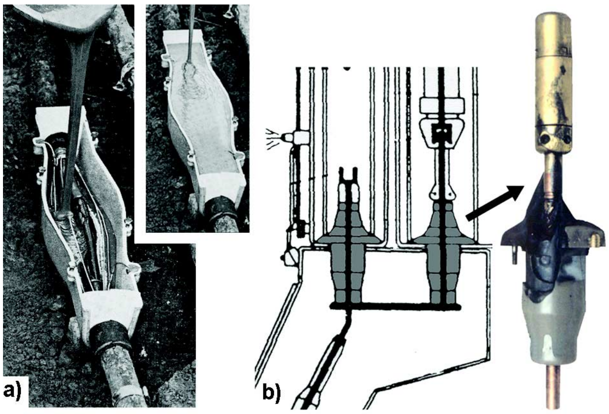

Figure 3. (a) Filling the cable joint with resin during installation, (b) The epoxy bushing in the switchgear assembly with an example of a failed bushing.

rameters are determined. With the parameter estimates, the statistical analytical functions can be determined. These functions can be used for reliability estimation and future failure prediction.

Case Study 1: Medium Voltage Resin Cable Joint

In the 1970s a specific type of resin cable-joint was used in three-phase, paper-oil insulated medium-voltage cables. These joints now contribute significantly to outage time because of breakdown of the resin insulation.

A testing program was started a few years ago. During this withstand test, HV is applied to the cable, which can result in a breakdown of the insulation of the joint. The advantage of this method is that the joints can fail under controlled circumstances, not resulting in power loss. The failed joint then is replaced by another type of joint. Normally, this is the procedure for joints with an infant mortality failure character rather than for joint populations with an aging problem. It is interesting to learn whether the population of joints shows infant mortality (despite its age) or an aging failure characteristic.

The available data will be discussed first. As a next step the failure data is used as input for statistical analysis. From this it can be seen whether the failure mechanism is caused by aging.

The results of the analysis are used to estimate the number of failures in coming years.

A comparison can be made between the number of expected failures and the number of occurred failures. Such an analysis provides answers on the effectiveness of the testing program, as mentioned above.

A replacement strategy is proposed that can have a positive effect on the expected number of failures. By comparing the replacement strategy (as usually applied for a population with aging failures) with the effect of the testing program (as applied now), the effectiveness of the testing program is shown.

A. Available Data

To get a general impression of the joint population, the total population of joints installed in the 1970s is compared with the population still in-service, see Figure 5.

It can be seen that the percentage of joints still in service decreases for joints installed after 1975. An average of 60% of the joints installed after 1975 have been replaced. Before 1975, approximately 35% of the installed joints were replaced. A distinct reason cannot be given for this difference. Multiple factors may have affected the number of replacements, such as:

- replacement of entire cable sections;
- changes in joint design, which can result in higher failure probability;
- testing of cable sections, in which failed joints have been replaced.

The failure reporting from the utility has been consistent since 2000. Before this time, separate, smaller regional companies existed, from which failure data are mostly lost or incomplete. The total numbers of reported failures for each year since 2000 are shown in Figure 6.

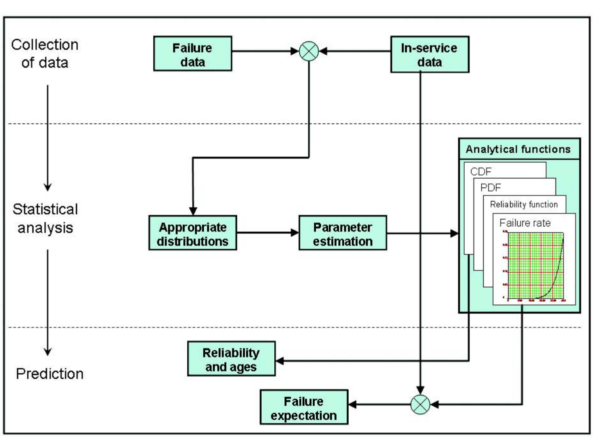

Figure 4. Analysis procedure flowchart as proposed by the authors to systematize the data analysis processes.

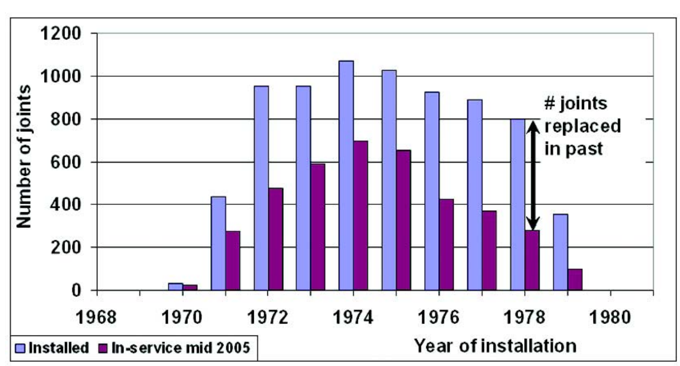

Figure 5. Number of resin cable joints installed and joints still in service mid 2005, with their year of installation.

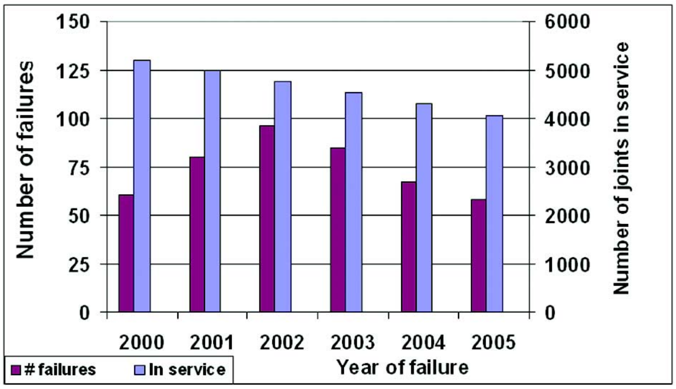

Figure 6. Number of reported failures and number of joints in service in 2000 to 2005.

In 2003, a change was made in failure recording. The year of installation of the failed joint was no longer recorded; only a rough estimation of the age was reported. For the joints that failed between 2000 and 2002, the years of installation are reported in the failure database, as shown in Figure 7.

These data are suitable for statistical analysis for which the age of the failed joints together with the age of the joints still in service are taken as input. Based on this analysis, the failure rate is calculated and compared with the failures that occurred in the years until 2002 and with those that occurred after 2002, as presented in Figure 6.

B. Statistical analysis

The reported failures of the years 2000-2002, together with the population of joints in service are used as input for the statistical analysis. The surviving joints also are taken into account, so we are dealing with a right censored data set. The median ranks of the probability of occurrence per age of failure are calculated, considering the suspended population. These values can be plotted on different kinds of probability paper, and the most appropriate statistical distribution is chosen to fit the data points. From the parameters of this distribution, the other analytical functions can be calculated as shown in Figure 4.

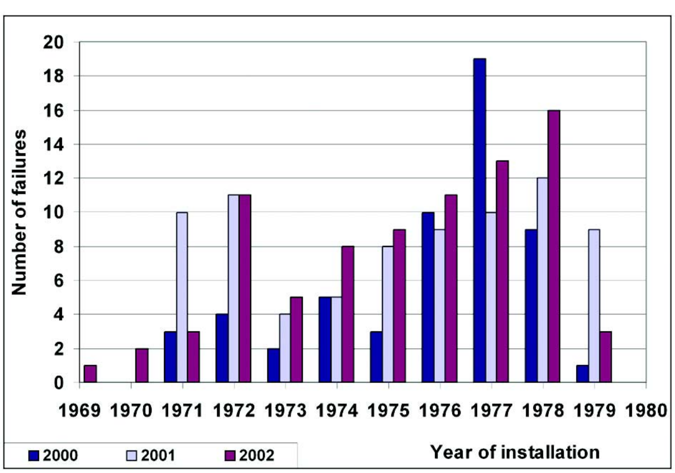

Figure 7. Number of reported failures in 2000–2002 with the year of installation of the cable joint.

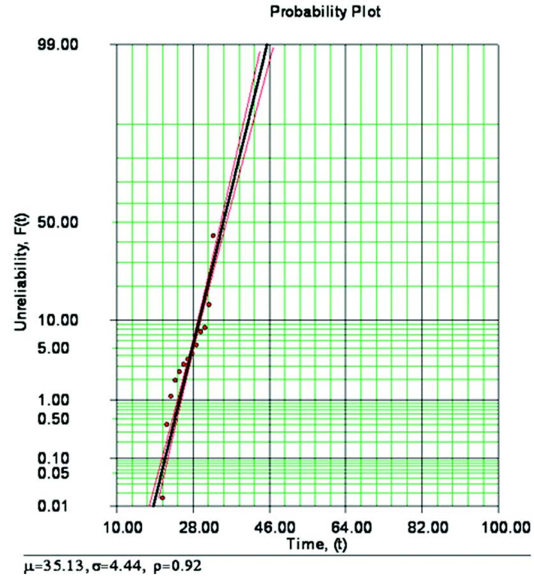

Figure 8. Failure data of the resin cable joint plotted on Weibull paper with the fitted CDF of the normal distribution together with the 90% confidence bounds.

In Figure 8, the cumulative distribution function of the fitted data is shown, using the normal distribution. The normal distribution is chosen because it gives the best fit to the data points according to the goodness-of-fit test. The correlation coefficient ρ and the Kolmogorov-Smirnov test are used to select the best-fitting distribution. The parameters of the normal distribution

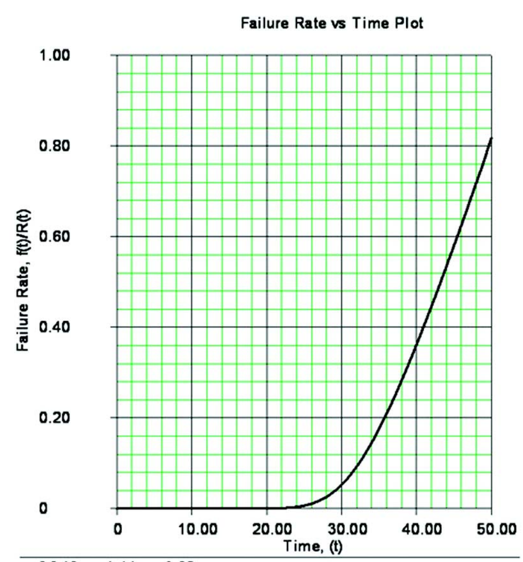

Figure 9. Failure rate function of the resin cable joints based on the fitted normal distribution.

are obtained using the least squares calculation method, resulting in a mean value $\mu = 35$ and a standard deviation $\sigma = 4.5$. The statistical precision of the analysis is indicated by confidence bounds. In Figure 8, the 90% confidence bounds are shown, which are relatively narrow because of the large amount of data.

The accompanying failure-rate function is shown in Figure 9. This failure rate is calculated with the failure-rate function of (3). For the normal distribution, this is written as:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2}}{\int_t^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2} dt} \tag{4}$$

C. Failure Expectation

With the failure-rate function of the resin cable joints and the known age distribution of the joints still in service, the expected number of future failures can be calculated. In addition, the calculated number of failures can be compared with the actual occurred failures. The expected number of failures $N_{f,e}$ is calculated as:

$$N_{f,e} = \sum_{i=0}^{Age\ oldest} \lambda(i) \cdot N_i \tag{5}$$

where $\lambda(i)$ is the failure rate value at age i, N_i = number of joints in service with age i.

Using Equation (5), the number of expected future failures can be calculated. For each year the population of joints in service gets 1 year older and the estimated failures from the previous year is subtracted from the population. This is shown in Figure 10 by the curve, expected failures without testing.

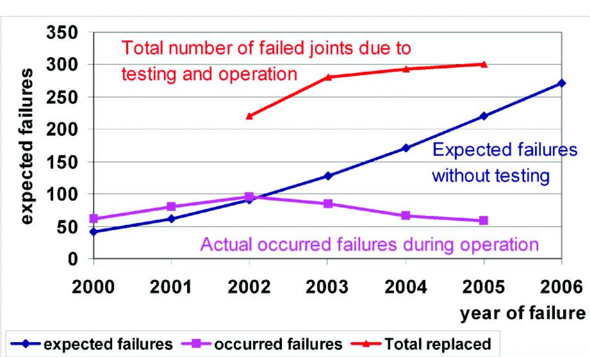

Figure 10. Number of occurred failures in 2000–2005, expected number of failures based on the analysis, and the total number of joints replaced in the period 2002–2005.

From Figure 10, it can be seen that the estimated number of failures based on the analysis are comparable with the actual number of failures in the period 2000-2002, shown in Figure 6. In 2002, the testing program was started in which a number of cable connections with one or more resin cable-joints were tested. The cable connections to be tested were chosen at random. Cable joints that failed during testing were replaced by a newer type of joint. The experience in the field shows that the joints which survive the test generally are free of failures for the next 4 to 5 years. The testing of joints influences the number of occurred failures during service in the years after 2002, as is clearly visible in Figure 10.

The number of failures that occurred after 2002, with the implementation of the test program, follows a decreasing trend. The number of expected failures without the implementation of the test program follows an increasing trend. Thus, the numbers of inservice failures after the implementation of the test program were positively influenced by the testing program.

D. Influence of a Replacement Strategy

The number of failures to be expected in coming years is influenced by the replacement strategy. For the resin cable joints, the analysis shows that aging can be pointed out as the main cause of failures. Because of this, an alternative replacement strategy would be to replace a certain number of the oldest joints in service every year. To see the effect of this replacement strategy, the expected failure development is analyzed for the case that different numbers of joints would have been replaced each year, starting in 2002. This year is chosen because of the start of the testing program that year. For this analysis it is assumed that the testing program had not taken place and joints were replaced only after a failure or as a result of preventive action.

Based on the statistical analysis, the influence of this preventive replacement is determined. This is done for the cases that each year, starting in 2002, 100 up to 750 of the oldest joints in service would have been replaced. Preventive replacement of the oldest joints would have had a positive effect on the number of expected failures, as can be seen in Figure 11. However, the expected failures still would be higher than the occurred failures. Two hundred joints replaced each year can be compared with the number of joints replaced due to the testing program.

This replacement schedule is not, however, as effective as the testing program. It can be concluded that, when each year 750 of the oldest joints would have been replaced, the expected failures would follow the real occurred failures. This means that almost four times the number of joints would have been replaced than the case with the testing program. This also would have resulted in the replacement of the total population of joints by 2008.

Another approach is to start the replacement at the beginning of 2006, because up to here all required data is available. To see what the influence is of this preventive replacement program, an estimate is made of the expected failures in coming years, based on the failures that occurred in 2005. Experience shows that a tested connection is free of failures in the 4 to 5 years after a test.

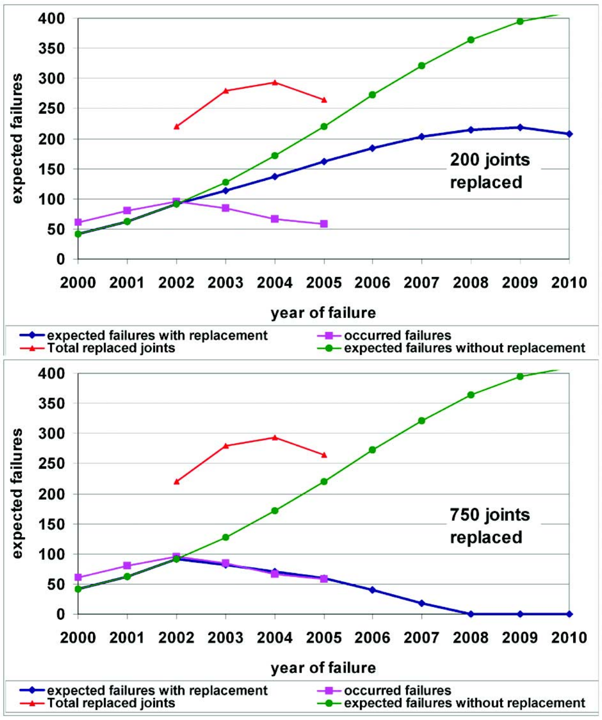

Figure 11. Effect of a preventive replacement strategy on the expected failures development.

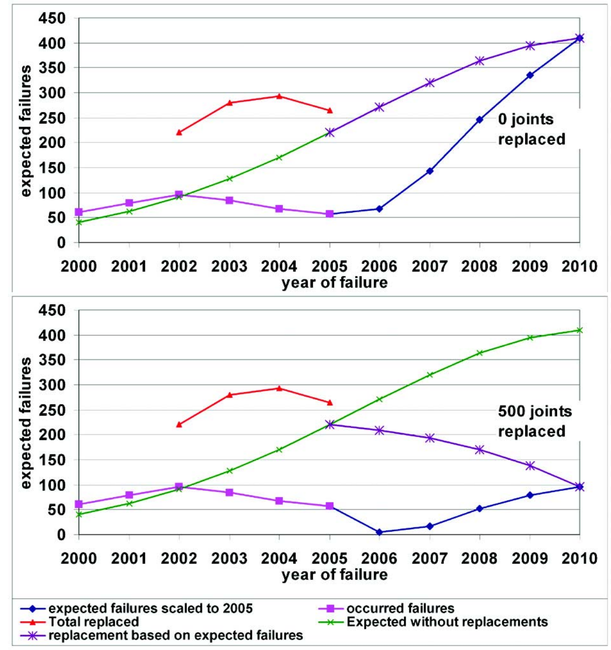

Figure 12. Number of expected failures with and without preventive replacement of 500 of the oldest joints starting in 2006, and the influence of preventive replacement on the unadjusted expected failure curve.

Based on this experience, the failure expectation can be adjusted. This is done by estimating the number of failures, taking into account that the testing and replacement of a cable connection influences the number of failures in the years following the end of the test program. However, this effect will slowly decrease, and eventually the effect of the testing program will disappear. The development of expected failures in coming years is shown in the top graph of Figure 12.

In recent years, almost all cable connections were tested. This is taken into account for calculating the adjusted number of expected failures as shown in Figure 12.

To see what the influence is of replacing the oldest joints in service, different numbers of joints to be replaced are considered. From Figure 12 it can be seen that a large number of joints has to be replaced to maintain the number of occurring failures of the previous years.

The failure estimation, based on the replacement of 500 of the oldest joints each year, first shows a decreasing failure expectation and later an increasing failure expectation. Replacing such a large amount of joints each year will result in a replacement of more than half of the total joint population by about 2010.

E. Conclusions

Based on the analysis of failure data of the resin cable joints, the following conclusions are drawn:

- Aging is the main reason for failure, the resin cable joints are in the steep slope of region III of the bathtub curve.
- The number of calculated, expected failures is comparable with the total number of actually occurred failures in the period 2000-2002.
- The effect of testing the cable connections is visible, when the number of expected failures is compared with the actual occurred failures. The number of occurred failures even decreased in the last years, and an increase was expected without the testing program.
- An active strategy of replacing a certain number of the oldest joints each year has a positive effect on the number of expected failures. The number of joints that should have been replaced in the previous years or have to be replaced in coming years to obtain the same effect as the testing program is much higher than the number of joints replaced during the testing program.

Case Study 2: Epoxy-Resin Bushings

A widely used type of circuit breaker in The Netherlands is the three-phase minimum oil-filled switchgear assembly. This type of switchgear was installed in the period 1965 to 1987. The different components of the switchgear assembly fail according to different failure modes. The maintainability and the possibility to determine the condition differ for each component. A component for which no maintenance or condition determination can be applied is the epoxy resin bushing of the switchgear assembly. These bushings are used to connect the energized parts between the different (oil filled) compartments of the switchgear assembly. The total amount of available data can be split into two datasets.

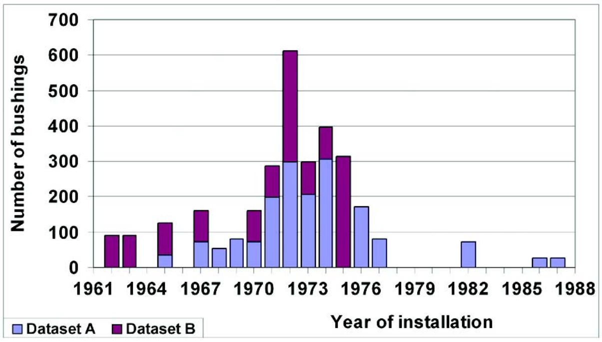

Figure 13. Total population of bushings in service for dataset A and dataset B.

A. Available Data

Four failures have been reported concerning the breakdown of epoxy-resin bushings in the switchgear. Compared with the total population, the number of failures is small; but the impact of a failure is high and the replacement of a bushing is costly. For dataset A, the ages of the population are exactly known. For dataset B, not all the exact ages of the components are known, and for part of the population in service, an estimation has to be made. The numbers of bushings in service for both datasets are shown in Figure 13.

It is to be noted that the experience with the 50 kV COQ switchgear assembly discussed here is based on the situation in The Netherlands. Elsewhere, very bad experiences have been reported for similar switchgear technologies that are or have been in service. Complete replacement programs have been undertaken. One of the reasons for this bad performance is that a bushing failure can result in an explosion and a fire in the total switchgear assembly.

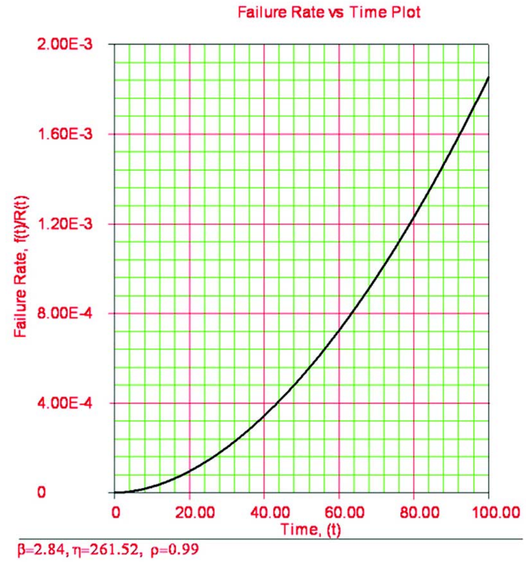

Figure 15. Accompanying failure rate function of the Weibull fit for the analysis with 4 failures of epoxy bushings.

B. Statistical Analysis

For dataset A, a failure analysis is performed, and the results fitted to a two-parameter Weibull distribution, see Figure 14. In comparison with the normal distribution used in case study 1, the correlation coefficient and the Kolmogorov-Smirnov goodness-of-fit test indicate that the Weibull distribution is the best fitted distribution for this data set. This results in a shape parameter: $\beta = 2.3$ and a high value for the characteristic life $\eta = 382$ years.

Because $\beta > 1$, it can be concluded that aging is the cause of the failures. However, the failure rate is increasing, but very

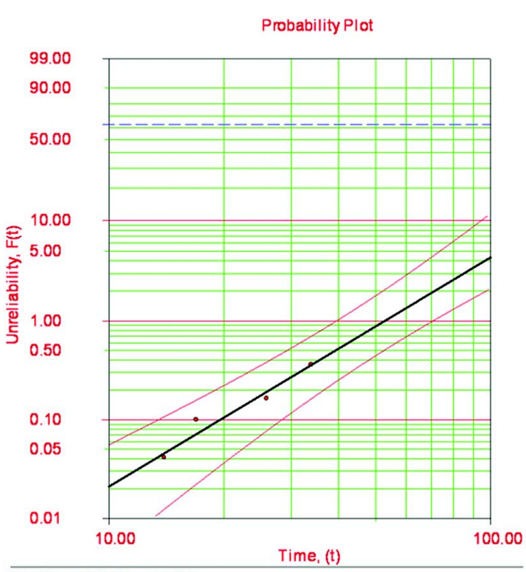

Figure 14. Two-parameter fitted Weibull CDF based on the four failures of epoxy resin bushings in dataset A with 90% confidence bounds on the fitted distribution.

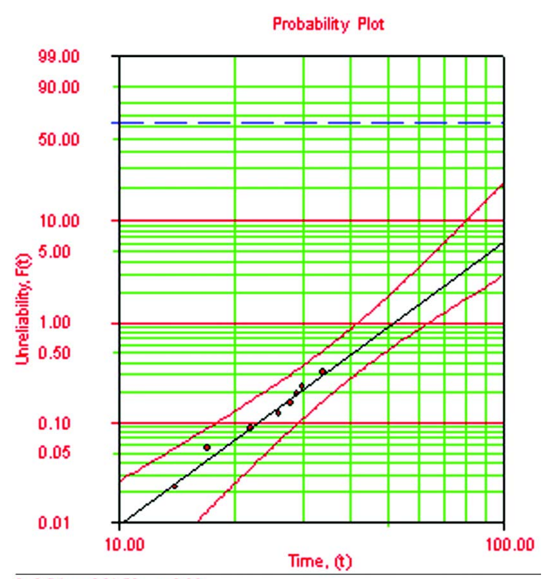

Figure 16. Two-parameter fitted Weibull CDF based on the eight failures of epoxy resin bushings in dataset A + B with 90% confidence bounds on the fitted distribution.

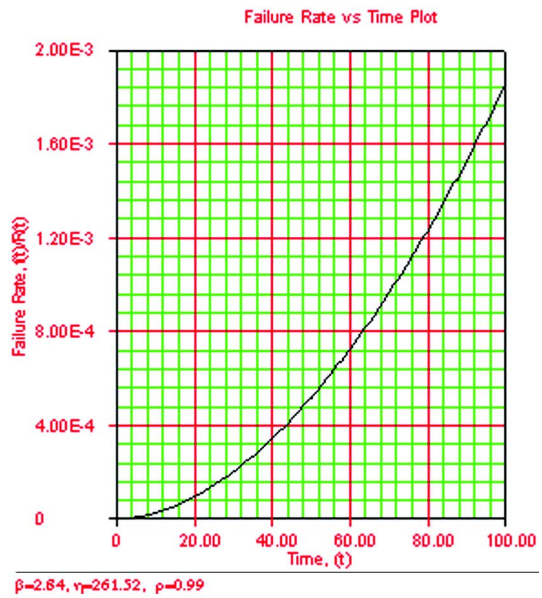

Figure 17. Accompanying failure rate function of the Weibull fit for the analysis with 8 failures of epoxy bushings.

slow and with relative low failure-rate values, as is shown in Figure 15.

For the total population (datasets A and B) together with the total of eight reported failed bushings, a second failure analysis was performed. In addition, the data points can be best fitted with the two-parameter Weibull distribution in this case. The cumulative distribution function shows a slope that is slightly steeper than in the case of four failures, as can be seen in Figure 16.

The Weibull parameters are estimated by means of the least squares method, resulting in a shape parameter β = 2.8 and a characteristic life η = 261 years, which is lower than in the four failure case. Consequently, a steeper failure-rate curve is obtained, but the values of the failure rate are once again relatively small, as can be seen in Figure 17.

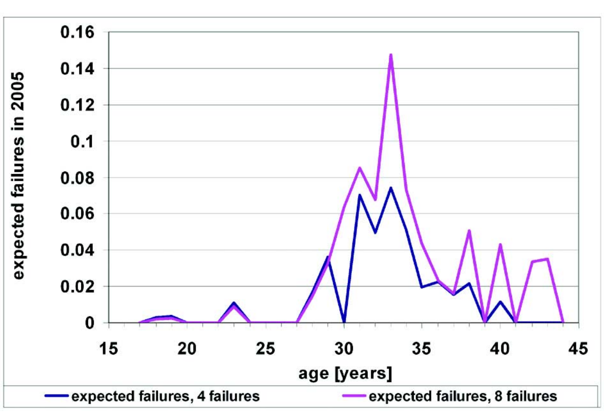

Figure 18. Development of expected failures in 2005 using the analysis of dataset A and both datasets (A+B).

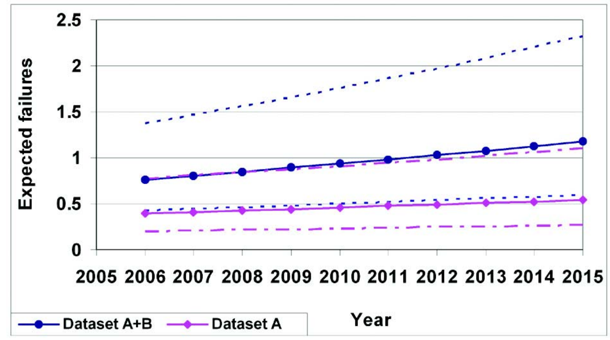

Figure 19. Total number of expected failures in the next years considering the analysis of both datasets (solid lines) including the 90% confidence bounds for each dataset (dashed lines).

From these two analyses, the Bx-lives can be obtained, together with the confidence bounds. B-lives are another way to represent the unreliability or CDF. The *x* is the unreliability in percent. In industrial design, B0.01 up to B10 lives are used together with the confidence bounds. The B1 life, or in other words, the age at which components have a reliability of 99%, is 53 years for the subpopulation (dataset A) with four failures. If the corresponding 90% confidence bounds are considered, the B1 life is between 40 and 71 years. For the case in which the entire population is considered (datasets A+B), the B1 life is 52 years, with a 90% confidence interval of 42 to 64 years. The B-lives for different percentages together with their 90% confidence bounds can be obtained from Figure 14 and Figure 16.

C. Failure Expectation

With the failure rates of both analyses together with (1), it is possible to determine the number of expected failures in the future. If the population of 2005 is considered with the age distributions of Figure 13, the expected failures per age can be determined. This results in a failure development as shown in Figure 18 for the cases of four and eight failures. In Figure 18, the total number of expected failures is shown for each age of the switchgear assembly in the year 2005.

The maximum number of expected failures is calculated for the population which now has an age of 33 years. This number is 0.074 for dataset A and 0.15 for the total population (datasets A+B), resulting in approximately one failure in 14 or 7 years. The failure expectation for 2005 is graphically shown in Figure 18.

The total number of expected failures in 2005 is the sum of the expected failures per age. The total number of expected failures in coming years is shown in Figure 19. From Figure 19, it can be seen that the expected number of failures is increasing slightly in coming years. The analysis always involves an uncertainty in the prediction of the number of future failures. The variation in the number of expected failures can be displayed by the confidence bounds. To visualize the variation, the 90% confidence bounds are shown in Figure 19. The large variation indicated by the confidence bounds can be explained by the relatively low number of failures used for the analysis.

D. Conclusions

Based on the analysis of failure data of epoxy bushings, the following conclusions are drawn:

- Statistical analysis of failure data is a useful tool for the prediction of future failures, even when the amount of failure data is small. This is particularly true when the ages of the components in service are included in the analysis as censored data. It has to be taken into account that the availability of more failure data gives a higher confidence level of the analysis.
- A very slow increase in failures can be expected in the coming years. Considering the age distribution of the total population, together with the results of the statistical analysis, it can be stated that the population is still young when only the failures concerning the epoxy bushings are taken into account. Nevertheless, for population A, an average of two failures in the coming 5 years are expected and a total of four failures for the populations A and B together.
- Aging can be considered as the main reason for failure; the bushings are in region III of the bathtub curve.

Discussion of Obtained Results and Conclusions

On the basis of the introductory remarks and the presented case studies, some additional statements need to be made.

- Statistical methods, also the simple ones, can be applied to support important maintenance decisions, using both the data obtained from diagnostic measurements and life data.
- For the case studies presented in this paper, the fundamental assumptions regarding the applicability of probabilistic methods are of importance: the homogeneity of obtained data, the independence of events under discussion, the stochastic characteristics of the processes under discussion. This last point is worth some special attention. The relatively long useful life (20-50 years) of power components like cable joints (Case Study 1) or high-voltage circuit breakers (Case Study 2) leads to different modes of wear-out and aging processes. In addition, it leads to the introduction of maintenance activities during the lifetime of the component. Such aspects can result in significant changes of time curves (e.g., event free time of a component [13]) of failure rates (bathtub curves), as presented in Figure 1.

In the end, the asset manager has to determine which strategy best fits the business values and the company's risk appetite.

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