A STATISTICAL APPROACH TO PROCESSING POWER TRANSFORMER FAILURE DATA

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ABSTRACT

Replacements of transformers are costly, especially when the replacement takes place before the (technical) end of life. The different failure modes that can take place in a power transformer can have different origins. If ageing can be denoted as the main cause for failure, the question then becomes to what extent ageing occurs.
By means of statistical failure analysis the ageing processes related to the ages of the transformers can be shown. As input for the analysis a population of power transformers with different ratings and different manufactures is used. Statistical analyses can be done for the total population as well for sub-populations, based on voltage level or transformer component. The failure data is fitted with mathematical statistical distributions and the accompanying parameters can be estimated. From the analysis it can be seen in what way the components are in their wear-out life and what can be expected for the future regarding failures. Although the population of power transformers is not uniform, statistical analyses can provide valuable information to help the asset manager in the decision process.

INTRODUCTION

Power transformers can be considered as one of the most significant parts in the electricity network. This involves that the transformer has a lot of attention by the asset manager of every electric utility. Replacement or repair of power transformers is costly and time consuming. But when the ages of the transformers which are now in service are considered, replacement will become necessary in the future.
To get an impression of the condition of the total transformer population, utilities develop a life cycle transformer management program. The management of the transformer population can be dived by three steps [1]:

1) Risk assessment of the transformer population(s) in service; which transformers are critical, important connections.
2) Condition assessment of the individual transformers; e.g. visual inspection, diagnostic measurements, monitoring.
3) Life cycle decisions about the future of the transformer: Is retirement, refurbishment, replacement or relocation necessary.

Another aspect of the management of transformers is to determine in what way spare transformers are needed to be able to replace a transformer in case of a failure resulting in a long term outage. If a spare transformer is not available for replacing a failed transformer, it is possible that the N-1 criterion is not fulfilled for a longer time. The N-1 criterion provides for each network that it has to be able to withstand the sudden outage of a failed network component at any time without intolerable violation of technical limitations or interruption of supply to any customer.
A way to get an overall impression of the state of the total transformer population, statistical failure analysis can be performed. The failures reported the last years are used as input for the analysis. In this paper the analysis will be discussed starting by showing the population now in service. This population can be split up in two sub-populations based on the voltage level (and power rating) of the transformers. The reported failures are also discussed and also the failures can be divided into sub-groups based on the type of failures reported. The failure data together with the populations in service are used to perform statistical analysis. From the analysis it can be seen whether failures occur in relation to the age of the transformers (ageing). The general approach is graphically presented in Figure 1.

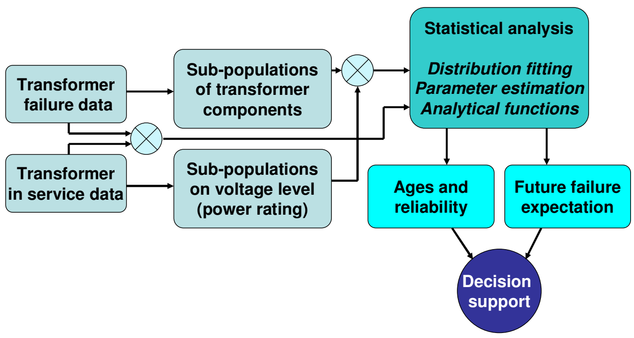


Figure 1 Approach of the analysis on power transformers

POPULATIONS OF POWER TRANSFORMER IN SERVICE

The analysis is performed for a population of power transformers with a power rating starting at 14 MVA up to 175 MVA. The service life of this population differs a lot due to the different installation years from 1950 up to now. The range of service life is from one up to 55 years. The numbers of power transformers installed with the years of installation is shown in Figure 2. From this figure it can be seen that a large part of the transformer population is installed between 1955 and 1980. The average age of the total population is 29 years.

A total population of almost 500 transformers is in service. The total population consists of different types of transformers. Groups of transformers can be distinguished. In this case this is done based on the voltage level:

- Group 1 transformers: Voltage levels of 150/50/10, 150/50, 150/20, 150/10, 110/20 and 110/10 kV.
- Group 2 transformers: Voltage levels of 50/10 and 50/6 kV.
- Booster transformers: Voltage level 10/10 kV.
- Other: Voltage level 20/10 kV.

The last two types are not taken into account in the analysis, because for these two categories only a few failures are reported.

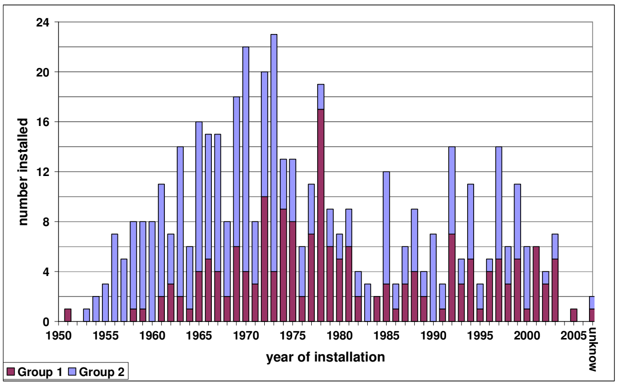


Figure 2 Total number of power transformers in service with their years of installation, the devission in the two groups is shown

The populations of Group 1 and Group 2 transformers with their years of installation are shown in Figure 2. By making these sub-populations it is possible to do statistical failure analysis on the whole population as well on the subpopulations. Failure behavior of these sub-populations can be different and this can influence the analysis of the total population. These two sub-populations differ a lot concerning type of transformer. This is important when the availability of spare transformers is considered. Differences in the results of the analysis between the two populations can be taken into account for the decision to obtain extra spare transformers.

FAILURE STATISTICS OF POWER TRANSFORMERS

An overall database of the complete population of the utility is available which reports failures of the past years. Failures are listed from the early nineties up to now. The age of the transformers at time of failure can be found in the database and this is used as input for the analysis. By reporting what the defect was it is possible to divide the failures in categories.

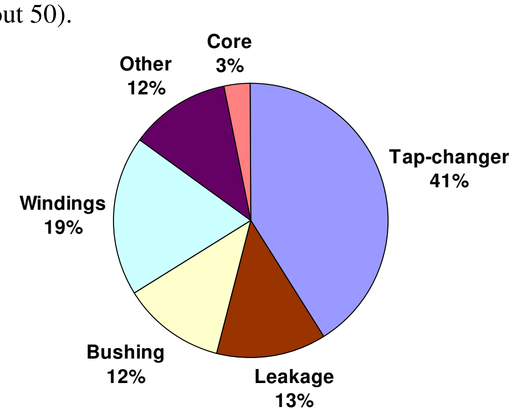
Failed components

The reported failures consist of different type of failures. This means that the failures can be divided into the different components. This is done by making groups of components according to Cigré [2]:

- Tap-changer: This includes the off-load as well the on-load tap changers
- Leakage: Problems concerning the tank and the dielectric fluid.
- Bushings
- Windings: Short circuit of the windings of a transformer
- Core: Problems concerning the magnetic circuit.
- Other: e.g. Temperature problems.

The occurrence of failures in power transformers as reported in [2] is graphically shown in Figure 3.

For the failures reported in the database of the transformer population a same graphical presentation can be made. For this the reported failures are grouped in the same way as described above. The failure statistics of Cigré consists of approximately 800 failures, the number of reported failures in the Continuon failure database is obvious much smaller (about 50).



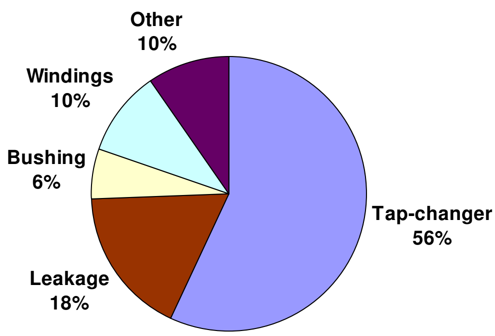


Figure 3 Failure statistics of different transformer components reported by CIGRE [2] (upper) and in the failure database (lower)

STATISTICAL FAILURE ANALYSIS OF LIFETIME DATA

Total population

For the statistical analysis the ages of the transformer failures and the ages of transformers still in service are used as input. To get a first impression the complete population together with all the reported failures is used to fit a statistical distribution.

The failure data can best be fitted with a two-parameter Weibull distribution, based on different goodness-of-fit tests (correlation coefficient, Kolmogorov-Smirnov). The estimated Weibull shape parameter β = 3.3 and the characteristic life or scale parameter η = 70. In Figure 4 the data points are shown with the fitted Weibull distribution. Also the 90 % confidence bounds are shown. The mean life of the total population regarding all type of failures is 62 years.

From the analysis the failure rate function can de derived. The failure rate is shown in Figure 4 together with the 90% confidence bounds. The rising failure rate function and the value of the Weibull shape parameter (β>1) indicates that the population of transformers is in the ageing part of its life cycle.

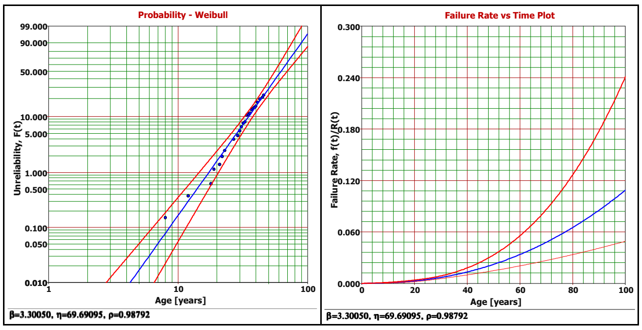


Figure 4 Fitted two parameter Weibull CDF (left) and the accompanying failure rate function (right) with the 90% confidence bounds for the total population

Sub-populations

The total population can be divided in two sub-populations. The division is made based on voltage level. This results in a population of Group 1 transformers with a voltage level above 50 kV and a population of Group 2 transformers with a voltage level equal to 50 kV.

First the population of Group 1 transformers is analyzed. The best fitted distribution is in this case the three-parameter Weibull distribution. The age distribution of the reported failures for this subpopulation shows that the youngest reported failure occurred at the age of 23. Because not the whole failure history is known, it can be possible that younger failures are unknown. These facts can explain the use of the three parameter Weibull distribution with the introduction of the location parameter γ. The Weibull parameters are estimated resulting in a shape parameter β = 2.8, scale parameter η = 36 years and the location parameter γ = 17 years, see Figure 5. The mean life of this subpopulation regarding the reported failures of this population is 49 years. Because the low number of failures the 90% confidence bounds are relatively wide. This can also be seen in the failure rate function with the 90% confidence bounds of Figure 5. The population of Group 1 transformers is in the aging state of its life cycle as can be seen by the rising failure rate function.

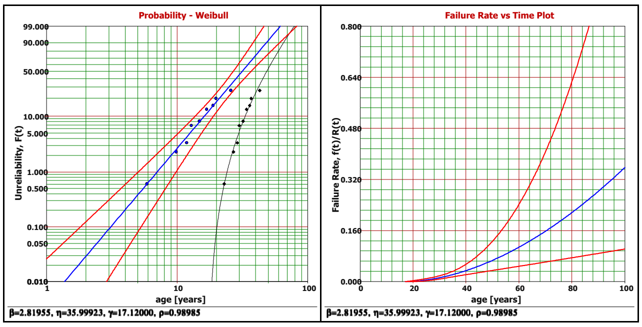


Figure 5 Fitted three parameter Weibull CDF (left) and the accompanying failure rate function (right) with the 90% confidence bounds for the sub-population Group 1

The same analysis as discussed above can be done on the Group 2 transformers. This subpopulation is larger and consists of more reported failures. According to the goodness-of-fit test, the two parameter Weibull distribution gives the best fit for this data set.

The Weibull parameters are estimated resulting in the shape parameter β = 2.8 and the characteristic life η = 80 years. The mean life is 71 years. Because of the larger amount of available failure data, the 90% confidence bounds are narrower compared to the analysis of the Group 1 transformers. This can also be seen in the failure rate function of Figure 6. The steepness of the failure rate function is lower compared to the failure rate function of the Group 1 transformers, but starts at earlier age.

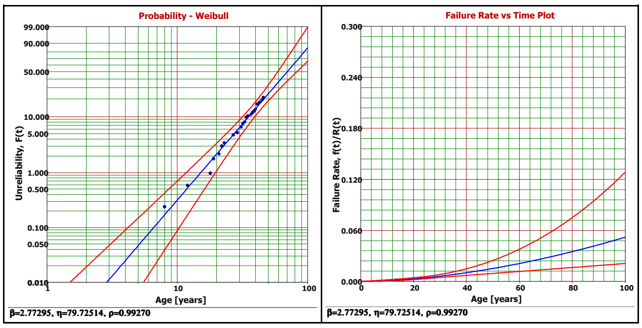


Figure 6 Fitted two parameter Weibull CDF (left) and the accompanying failure rate function (right) with the 90% confidence bounds for the sub-population Group 2

Discussion

If the total population is considered, it can be seen that the failure probability will increase by an increasing age of the transformers. The same trend can be seen when the two sub-populations based on voltage level are considered. The failure rate of the Group 1 transformers shows a steeper trend compared to the failure rate of the Group 2 transformers. For the Group 1 transformers the fitted three parameter Weibull distribution indicates that no failures occur before the age of 17 years.

Every industry uses B-lives indicating a certain level of reliability based on the age of a component. In the world of engineering the used B-life starts mostly around B10. This means that 10 % of the total population will fail at a certain age and that 90 % survives. Different industries use different values for an acceptance value for unreliability/reliability depending on the criticality of a failure. These B-lives can also be used to compare analysis. To see the differences between the reliabilities the B-lives and mean life (B50) from the (sub-) populations can be compared with each other. This is shown in Table 1.

Table 1 B-lives and mean live resulting from the analyses of the total- and sub-populations, in parenthesis the upper and lower values of the 90% confidence bounds.

	Total population [years]	Sub-pop. Group 1 [years]	Sub-pop. Group 2 [years]
B1 life	17 (15-21)	24 (22-27)	15 (12-20)
B10 life	35 (33-38)	33 (31-36)	35 (32-39)
Mean life	63 (56-70)	49 (44-55)	71 (60-84)

From the table it can be seen that for a reliability of 99% (B1 life) the Group 2 transformer shows failures at a lower age compared to the Group 1 transformer. The mean life however is higher for the Group 2 transformer. This difference is due to the fact that the age of the youngest failure is occurring after 20 years. The ages at lower values of reliability are lower for the Group 1 transformer compared to the Group 2 transformers.

The analysis can also be performed on component level. The most critical components are the tap-changer and the windings. The failure data of these components is used for the analysis for the two sub-populations. The fitted Weibull distributions show that failures occur due to ageing. The failures of the tap-changer start at younger ages compared to the failures of the windings.

FAILURE EXPECTATION BASED ON THE ANALYSIS

The different analyses as discussed before can be used to perform a failure prediction. The failure rate function together with the population in service is used to estimate the development of failures in the future.

Firstly the failure expectation is done for the total population of transformers and for the two sub-populations. This results in the failure expectation as shown in Figure 7. The number of expected failures of the total population is around 4 with 90% confidence bounds of 3 to 6. If this is related to the previous years it is comparable with the average number of failures occurred in former years. The number of expected failures of the two sub-populations is also comparable with the average of the occurred failures of the last years. If the number of expected failures are taken together the number is slightly higher than that of the total population but lies under the 90% upper confidence bound.

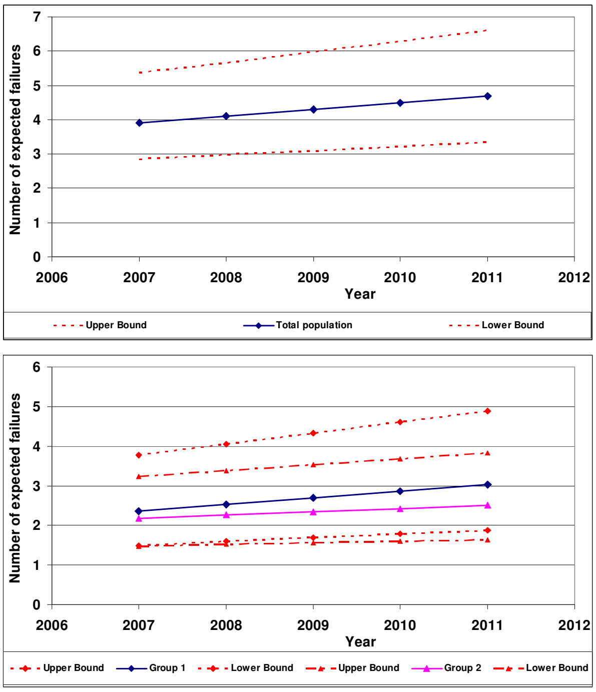


Figure 7 Number of expected failures in coming years together with the 90% confidence bounds for the total population (upper) and for the two sub-populations based on voltage level (lower)

The analysis of the different components from the two sub-populations can also be used for a failure expectation.

CONCLUSIONS

Based on the analysis it can be concluded that the failures in the population of power transformers are a result of ageing. The number of expected failures is stable and comparable with the past years. The spare transformer policy, that showed to be successful in the past, can be continued in the near future, e.g. ten years, without impairing the system's reliability.

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