ASSESSMENT OF POWER TRANSFORMER RELIABILITY

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Abstract: Power transformers are one of the most important parts of power systems and often the most valuable asset in a substation. Understanding how and when transformers are likely to fail is a critical point in the asset management of large networks. Due to aging and inadequate maintenance some critical failures in power transformers may occur. Thus, the aim is to reduce the failure rate as low as possible. One way to minimize failure probability is the analysis of old failures and their conditions in order to understand the reasons for severe failures and to improve maintenance procedures by means of this knowledge.

In this contribution the results of a failure data survey of 20 utilities in Germany, Swiss, Austria and the Netherlands based on a newly developed questionnaire are presented. The investigated transformer population covers more than 23800 unit-years and reveals a failure rate of 0.3% for 110kV and 0.6% for 220kV and 380kV for major failures. The hazard curve function shows considerable low failure rates for a transformer age below 30 years. Tap changer and windings are with one third each the main components leading to major failures.

1 INTRODUCTION

Power transformers are one of the important parts of power systems and often the most valuable asset in a substation. Understanding how and when transformers are likely to fail is a critical point in the asset management of large networks. Due to aging and inadequate maintenance some critical failures in power transformers may occur. Thus, the aim is to reduce the failure rate as low as possible. One way to minimize failure probability is the analysis of old failures and their conditions in order to understand the reasons for severe failures and to improve maintenance procedures by means of this knowledge.

An international survey on failures in large power transformers in Service was launched in March 1978 and was limited, for practical reasons, to the countries represented in CIGRE Study Committee 12 (power transformers, now A2). The survey involved transformer and reactor units designed for networks with a highest system voltage of not less than 72 kV, without any limitation on rated power, not older than 20 years, and installed on generation, transmission and distribution systems [1].

In Germany, official statistics are compiled that present the analysis of disturbances from participating utilities in the country. All disturbances are recorded in a standardized way. The main objective of this survey is the systematic collection of data on the availability and disturbances of the electrical power supply. So, main figures are frequency, duration and extent of interruptions. Detailed statistics about the failure location in the respective equipment, failure cause or mode and repair activities are not included. Therefore the benefit of this statistic regarding asset management is limited. [2, 3]

In contrast to this a questionnaire was developed by the CIGRE working group A2.37 (Transformer Reliability Survey) which constitutes a helpful tool to collect utility failure statistics in a standardized way [4, 5]. Beside information about the population under investigation failure data is collected for various groups of transformers in terms of failure locations, failure causes, failure modes, actions, external effects and others. Thus valuable information for asset management purposes can be achieved.

In this contribution the results of a failure data collection in Germany, Austria, Swiss and the Netherlands are presented based on the newly developed questionnaire.

2 DATA ACQUISITION

2.1 Methodology

The data used in this contribution are acquired by means of the reliability questionnaire form of CIGRE WG A2-37. Each utility filled a questionnaire form and all the answers were collected in a database. In order to achieve a maximum security and anonymity, the failure data were anonymized by a code on the basis of the geographical location and a sequential number.

In this survey failure data of transmission, distribution and generator-step-up transformers with operating voltage of 110kV, 220kV and 380kV were analysed.

2.2 Investigated Population

The questionnaire consists of three major sheets. The first sheet presents general information about the population of the operating transformers for the indicated reference period. Also, voltage ratio, rated power, typical loading and some other specifications for different applications of transformer units are available in this section. The other sheets of questionnaire submit failure data, essential definitions and failure analysis.

For each utilities a reliability questionnaire form exists which contains mentioned data. To be exact it is required to summarize all these forms into one single unified form.
The resulted unified form shows the number of applications based on their voltage throughout Germany, Austria, Swiss and Netherlands.

The characteristics of transformers from these countries are in terms of age and condition of population so similar that they have been classified in same category.

The analysis takes 112 failures within the last 11 years into account. All the failures are analyzed relating to a total population of more than 23800 unit-years. The investigation results are presented in term of external effects of failures, failure location, failure mode, failure cause and the action that was taken after failure. The following table shows the population information investigated in this contribution:

Table 1: Investigated population data of the transformers dependent on system voltage and application

POPULATION INFORMATION	**HIGHEST SYSTEM VOLTAGE**		
Application	**110kV**	**220kV**	**380kV**
Substation - Distribution	1292	0	0
Substation - Transmission	73	581	478
Power Station - Generator Step-Up	66	127	73

Because of limited failure data for generator step-up units, the following failure data analysis was not performed dependent on the application of the power transformer. Having a larger database it is planned to do a more specific analysis also taking the application and voltage class into account [4].

2.3 Failure data

The collected failure data account for major failures only. To clarify the meaning of failure, some terms are given according to the definitions within CIGRE WG A2.37 as follows:

Failure
Any unscheduled situation which requires the equipment to be removed from service for investigation, remedial work or replacement is a failure. Failure can be divided into minor and major failures both *with* forced and scheduled outages.

Major failure
Any situation which requires the equipment to be removed from service for a period longer than 7 days for investigation, remedial work or replacement is a major failure. Where repairs are required, these involve major remedial work, usually requiring the transformer to be removed from its plinth and returned to the factory. A major failure would require at least the opening of the tank, including the tap changer tank or an exchange of bushings. Also a reliable indication that the condition of the transformer prevents a safe operation should be counted as a major failure if remedial work (longer than 7 days) is needed for restoring original service capability (e.g. detection of strong PDs).

Minor failure
A minor failure requires remedial work that lasts shorter than 7 days.

After receiving the completed forms from utilities the data was checked and adjusted as follows:

- To have a uniformed survey, just the failures after year 2000 are counted.
- 20 utilities submitted data with different reference periods. The smallest reference period was 5 years.
- There were some data with nominal voltages less than 69 kV, in this case the failures were not counted.
- Bushings failures are assigned to major failures although the repair time was partly given as less than 1 week.

According to these preconditions, the investigation contains 112 major failures within 20 utilities from Germany, Austria, Swiss and the Netherlands.

3 DATA ANALYSIS

3.1 Failure rate

Failure rate

To determine the failure rate, the following formula is used [1]:

$$\lambda = \frac{\sum_{1}^{i} n_i}{\sum_{1}^{i} N_i} \cdot 100\% \qquad (1)$$

Where:

n_i = Number of transformers that failed in the i^{th} year

N_i = Number of transformers in service during the i^{th} year

For the calculation of failure rates a constant transformer population was assumed for the investigated time period.

The calculated failure rates are given in table 2 dependent on the voltage level. These results agree fairly well with the failure rates given in [2], where the failure rate is 0.31 % or the 110 kV units and 0.64% for the 220 kV and 380 kV units. The increase of failure rate with increasing voltage is obvious.

Table 2: Failure rate analysis of power transformers as a function of voltage class (Years from 2000 to 2010)

Voltage level	110 kV	220 kV	380 kV
Number of failures	36	44	32
Transformer years	11474	7111	5226
Failure rate (%)	0.31%	0.62%	0.61%

In [1] a general failure rate, irrespective of the voltage class and function of the units was given of the order of two percent. Reason for this deviation could be the different investigated population and taking into account also failures with downtimes of less than one week.

Table 3: Failure rate analysis of power transformers (transmission and distribution) as a function of voltage class (Years from 2000 to 2010)

Voltage level	110 kV	220 kV	380 kV
Number of failures	34	40	20
Transformer years	10748	5756	4482
Failure rate (%)	0.31%	0.69%	0.45%

In tables 3 and 4 the failure rates are shown dependent on the application of the transformer. It has to be considered that the investigated population and consequently also the number of failures of generator step-up units were quiet low. Therefore the failure rate of 1.61% for 380 kV G.S.U. is statistically not proven.

Table 4: Failure rate analysis of generator step-up transformers as a function of voltage class (Years from 2000 to 2010)

Voltage level	110 kV	220 kV	380 kV
Number of failures	2	4	12
Transformer years	726	1355	744
Failure rate (%)	0.28%	0.30%	1.61%

3.2 Hazard curve

There are some useful reliability functions to analyze the failure situation dependent on transformers age. Calculating the failure rate for ever smaller intervals of time, results in the hazard function. It shows the momentary probability of a failure dependent on the transformer age. In order to calculate the hazard rate the age distribution of all transformers is required. Due to simplicity reasons this age distribution is unfortunately not included into the used questionnaire. Therefore the transformer age distribution of the investigated population is calculated by using the age distribution of a utility participating in this survey as a reference for the 220kV and 380 kV voltage classes. Assuming that the transformer fleets of the other utilities have a similar age distribution in these voltage classes – which is very probable -, the full transformer age distribution can be calculated by scaling up the data of the reference utility. The achieved cumulative distribution of operational years of the investigated population in the voltage classes 220KV and 380 kV is shown in figure 1.

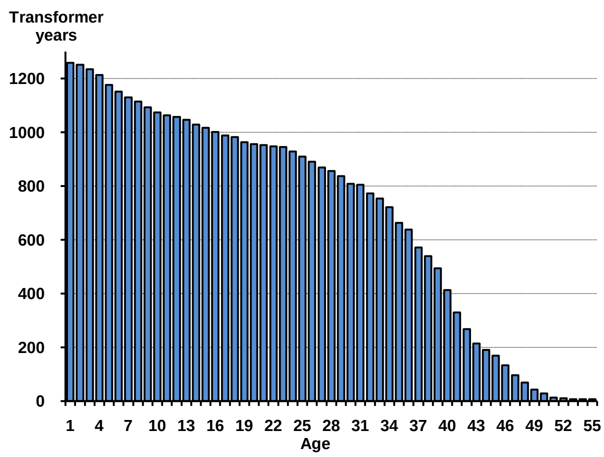

Figure 1: Cumulative distribution of operational years of investigated transformer population (220kV and 380 kV)

The hazard function is computed using the information from figure 1 and the following formula:

$$H(T) = \frac{f(T)}{N(T)} \cdot 100\%$$

$H(T)$ **:** Failure hazard rate in percentage
$f(T)$ **:** Number of failures at age interval T
$N(T)$ **:** Number of transformers in operation and surviving at age interval T

In figure 2 the hazard function is shown as a dotted line. In order to obtain a better interpretation of the results an averaged curve is provided using a five year moving average method.

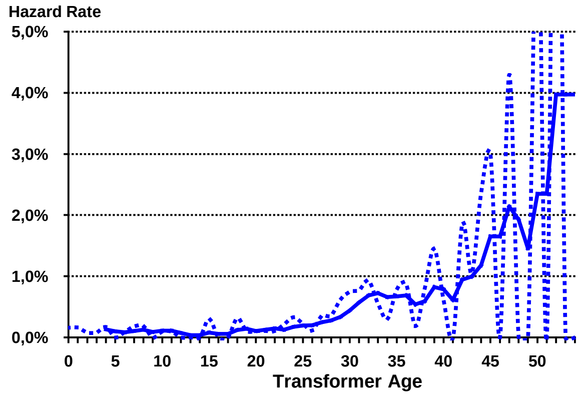

Figure 2: Failure hazard rate (dotted line) and five period moving average of failure hazard as a function of transformer age (220kV and 380 kV)

Below 30 years the failure rate is around 0.2% and therefore considerable low. Especially at the beginning of the operational life no period of particularly high failure rate could be observed that could possibly indicate design or manufacturing problems. At an age of 30 years the failure rate increases to an order of 0.7%. After an age of 40 years the hazard curve is increasing strongly to levels of far beyond 1%, which can be associated with end of life wear-out failures. It has to be regarded that for transformer ages above 40 years the operational experience is low. Therefore the calculation of hazard rate is statistically inaccurate, which can be seen by the peaks in the dotted curve in figure 2.

The hazard curve for generator step-up units only is not shown. The small investigated population and the low number of failures would give a result which is statistically not valid. But there are indications that the increase of failure rate starts some year earlier.

3.3 Failure location analysis

The failure data of the full population were analysed as a function of the primary location (component) in the transformer where the failure was initiated (Fig. 3).

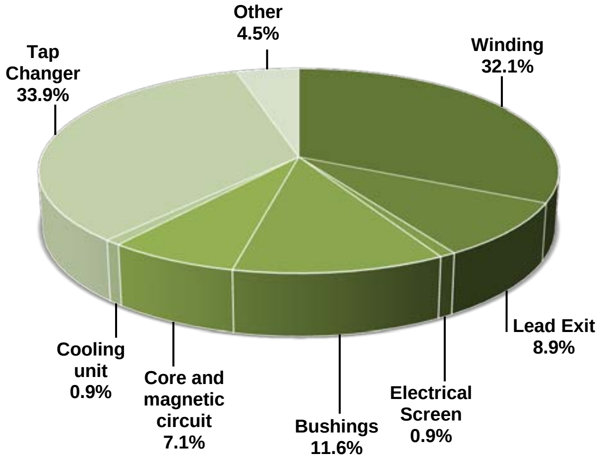

Figure 3: Failure location analysis based on 112 major failures between 2000 and 2010

Like in former surveys major failures are originating from several transformer components. Tap changer and windings are with one third each the main reasons for major failures. Bushings, lead exits and core are listed with a minor percentage as a reason for major failures. This result agrees fairly well with the statistics from 1983, if only failures with downtimes longer than one day are regarded [1].

3.4 Failure mode analysis

Information about the failure mode was also collected in the questionnaire which describes the nature of the failure illustrating what actually happened when the failure occurred. The definitions of the failure modes are according to [6]. Dielectric failure means PD, tracking, flashover. Electrical failure means open circuit, short circuit, poor joint, poor contact, ground deterioration, floating potential.
There is no single prominent failure mode. The categories of dielectric and electrical are with 27% each the most dominant (Fig. 4).

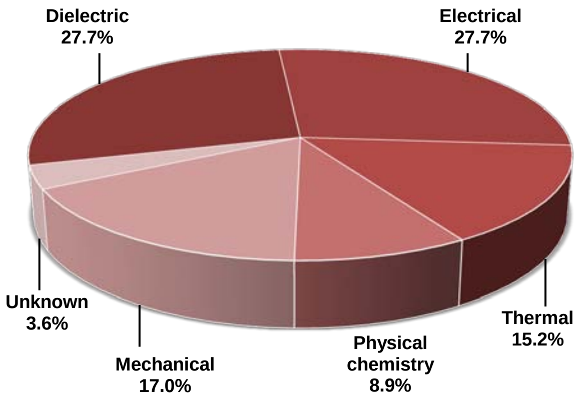

Figure 4: Failure mode analysis based on 112 major failures

3.5 Failure cause analysis

The circumstances during design, manufacture or operation that led to the failure are analysed. Because it is quiet difficult to determine the root cause of a failure, 25% are unknown causes. Among the different failure causes aging of transformer is with a contribution of 17.9% the most mentioned one. Astonishingly design and manufacturing are mentioned quiet often as a failure cause. This cannot be proven by the quiet low failure rate during the first 30 years of operation. Lightning and overvoltage are almost negligible as failure cause. An explanation is that almost all transformers in the investigated population are protected by surge arresters.

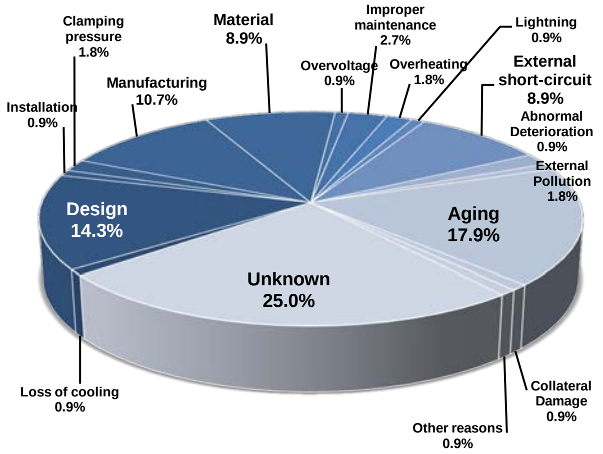

Figure 5: Failure cause analysis based on 112 major failures

3.6 External effects analysis

In figure 6 the various external effects which are caused due to the transformer failures are shown. Most of the major failures do not result in external effects (88.4%). Some other external effects which are detected in some cases are “Fire” with 6.3% and “Explosion or Burst” with 2.7%.

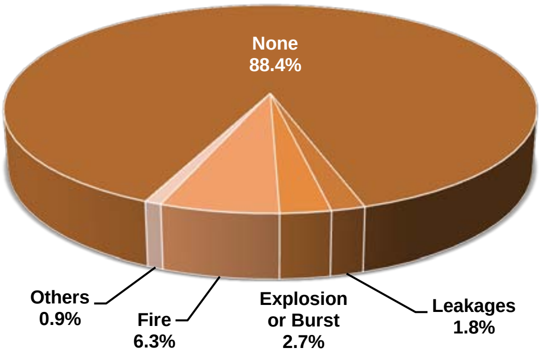

Figure 6: External effects of 112 transformers major failures

3.7 Action analysis

The actions taken after a major failure are depicted in figure 7. It can be explicitly seen that except the scrapped portion of transformers (35.7%), 24.2% of the failed ones were repaired onsite and 39.3% were repaired in a workshop.

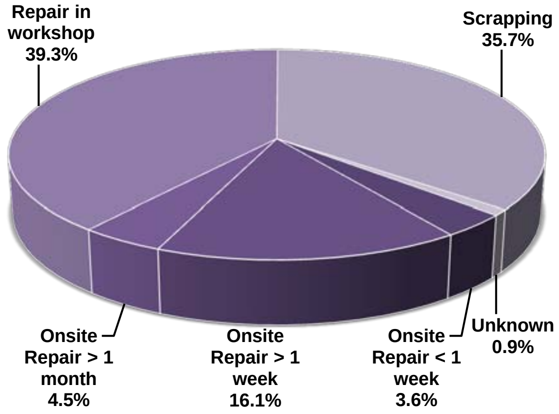

Figure 7: The analysis of the actions taken after 112 transformers failure

Figure 8 and 9 show the failure location of scrapped and repaired transformers respectively.

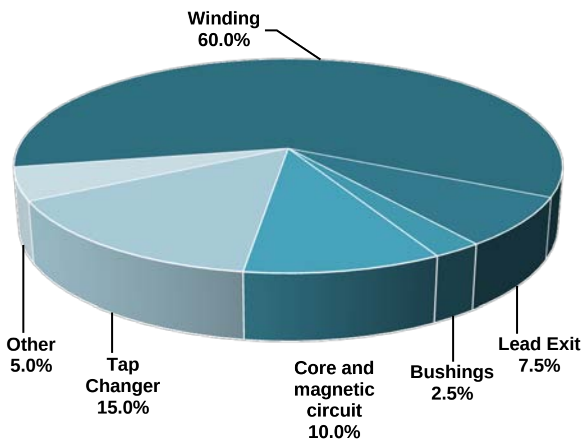

Figure 8: Failure location analysis of 40 scrapped transformers

Due to their impact winding failures lead normally to a situation where the failed transformer is scrapped. On the other hand tap changer and bushing failures are normally repaired.

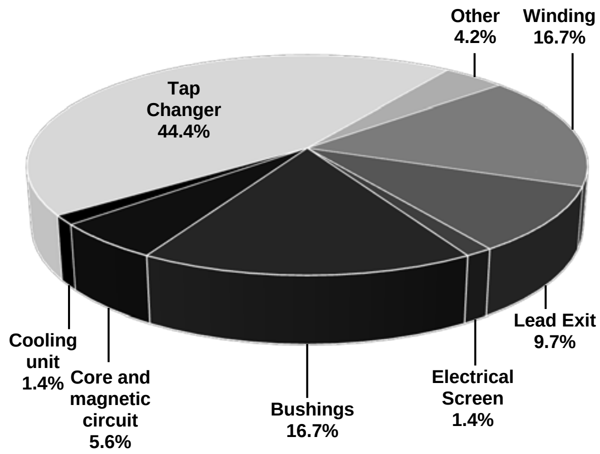

Figure 9: Failure location analysis of 72 repaired transformers

4 CONCLUSION

A questionnaire was developed by the CIGRE working group A2.37 (Transformer Reliability Survey) by which utility failure statistics in a standardized way can be collected. In contrast to several public available statistics the results of this questionnaire deliver valuable information which can be used for asset management of power transformer fleet. Thus transformer failure data can be analysed and interpreted for various types of transformers in terms of failure locations, failure causes, failure modes, actions, external effects and failure rates in transformers.

The presented results of the performed failure data survey are based on a population of 2690 transformers with more than 23800 unit-years and 112 major failures in Germany, Swiss, Austria and the Netherlands. They show a failure rate of 0.3% for 110kV and 0.6% for 220kV and above. The hazard curve function shows considerable low failure rates for a transformer age below 30 years. Tap changer and windings are with one third each the main reasons for major failures. Winding failures lead normally to scrapping of the transformer whereas tap changer and bushing failures are mostly repaired.

5 ACKNOWLEDGMENTS

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6 REFERENCES

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