COMPARING THE RELIABILITY OF OLDER AND NEWER TRANSFORMER DESIGNS

A Dissertation Presented

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DECLARATION

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ABSTRACT

This dissertation describes the findings of an investigation that was conducted to determine if the reliability of older designs was significantly different from newer designs, and whether the observed differences (if any) were the result of developments in design, manufacture and technology of transformers during different periods.

Examples from the literature demonstrate an ongoing debate in the transformer industry where two schools of thought exist, the one claiming that older transformer designs are more reliable than newer ones, and the other that newer designs are more reliable. Units from different periods of design and manufacture have yielded different failure rates, and could be linked to different periods of transformer reliability.

Thorough literature surveys were conducted to determine the trends in reliability within manufacturing periods, and to determine the developments in transformer design, manufacturing and technology in manufacturing periods. The South African transformer failure data was analysed and compared with the identified trends.

Trends in reliability have shown that the hypothesis was supported by some results and partially supported by others. Where high reliability was maintained in units from both manufacturing periods, it was attributed to constant developments in technology and manufacture. Where low reliability was maintained in units from both manufacturing periods, it was attributed to lack of developments in technology. Where reliability differed, the older designs appeared to be more reliable.

In summary, the hypothesis was found to be partially valid, but not in the sense that the overall reliability of groups of transformers could be predicted from a knowledge of their year of manufacture. Changes in design methods, materials, manufacturing details and the environment have affected the reliability of transformer components in different ways and the overall reliability does not appear to have changed much. There is insufficient data from recently manufactured transformers to establish the effects of the most recent technology developments on the reliability. Further, the analysis has shown that confounding factors such as repair might affect the apparent reliability, if not accounted for rigorously.

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ABBREVIATIONS

AAFR	: Annual Average Failure Rate
ABB	: Asea Brown Boveri
AEP	: American Electric Power
BSI	: British Standards Institution
CD	: Complete Data
CDF	: Cumulative Distribution Function
CIS	: Commonwealth of Independent States
Dx	: Distribution
EHV	: Extra High Voltage
FR	: Failure Rate
GEC	: General Electric Company
GSU	: Generator Step-up
Gx	: Generation
HP	: Hazard Plotting
IEC	: International Electrotechnical Commission
IFR	: Instantaneous Failure Rate
IEEE	: Institute of Electrical and Electronic Engineers
kV	: Kilo Volt
MCD	: Multiply Censored Data
mm	: Millimetre
MR	: Maschinenfabrik Reinhausen
MVA	: Mega Volt Ampere
MW	: Mega Watt
PDF	: Probability Density Function
RF	: Relative Frequency
SC	: Study Committee
Tx	: Transmission
UK	: United Kingdom
USA	: United States
US-N	: United States - National
USSR	: Union of Soviet Socialist Republics
WG	: Working Group
ZTZ	: Zaporozkii Transformatornii Zavod

CHAPTER 1: INTRODUCTION

1.1. PROBLEM STATEMENT

Transformers are an integral part of power systems and their reliable operation directly impacts that of the whole network.

To date, the only international survey on large power transformer failures was published in 1983 [Bossi, 1983]. The failed units were classified according to voltage level, age and application, and for each class, corresponding failure rates were calculated. The survey concluded that the average failure rate of transformers may be regarded as 2 % across all voltage categories. Since then, this statistic has become an international benchmark in the transformer industry for the failure rate performance of transformers. However, this survey was based on transformer failures occurring in the period 1968 to 1978, and should therefore only be valid for comparison with units designed and manufactured prior to and including 1978, excluding the post 1978 build.

In a study of the reliability of single phase generator transformer sets in the United Kingdom, the failure rate for units failing in the period 1974 to 1994, post 1974 build, was reported to be 1.2% [Hall, 2006]. This was an improvement in failure rate which stemmed from initiatives in terms of specification, design and manufacture, to enhance the reliability of the transformer fleet, after the poor experience with three phase units during 1966 to 1974, the pre 1974 build. Since 1995, the failure rate of single phase transformers showed further improvement to 0.6%.

Higher failure rates were observed in newer 765kV transformers over the period 1977 to 1986 in the post 1977 build, at a utility in the United States [Kogan, 1988, Wagenaar, 1994]. Lower failure rates in units manufactured before 1977 have been attributed to the fact that manufacturers built more margins into the designs by testing units at higher lightning and induced test levels than required by the specification.

These examples demonstrate an ongoing debate in the transformer industry where two schools of thought exist, the one claiming that older transformer designs are more reliable than newer ones, and the other that newer designs are more reliable. Different periods of design and manufacture have yielded different failure rates, and could be linked to different periods of transformer reliability.

1.2. RESEARCH HYPOTHESIS

Using data for transformer failures in South Africa, it is proposed that the reliability of older transformers can be shown to be significantly different from the reliability of newer units, and that this is a result of the differences in design, manufacture and technology during different periods.

Thus, this dissertation will compare the failure statistics according to periods of transformer design and manufacture.

1.3. RESEARCH QUESTIONS

The following research questions were formulated to assist in testing the hypothesis:

- How, and to what extent can transformer reliability be determined from the available failure statistics?
- What trends can be observed in the reliability/failure of transformers according to different manufacturing periods?
- How did developments in design, manufacture and technology influence transformer reliability statistics?
- Are there differences between the experience of transformer reliability in South Africa and in other countries?
- Are older designs more reliable than newer transformer designs?

1.4. DISSERTATION LAYOUT

Chapter 2 reviews transformer reliability as presented in the literature, with emphasis on recommendations for reliability practices in the industry, definitions and terminology associated with reliability, and statistics from available reliability surveys. The objectives are to determine how reliability is measured, and to identify trends in reliability (or failure) of transformers with manufacturing periods.

In chapter 3, the developments in transformer design, manufacture and technology, as presented in the literature, are reviewed with the aim of assessing to what extent developments influenced the trends in reliability (or failure) of transformers identified in chapter 2. Developments in the specification of transformers in South Africa are also discussed.

Chapter 4 provides a literature review of statistical analysis methods as a reliability measure ,in particular, looking at the underlying assumptions of data analysis, calculation of failure rates, four primary concepts (probability density function, cumulative distribution function, survival function and the hazard function), and non parametric data analysis techniques.

In chapter 5, recommendations from international standards and guidelines on the treatment of failure data (definitions, data collection and classification) are applied to transformer failures in South Africa, in preparation for the subsequent analysis. Based on the collected data and times when changes were implemented, the impact in the specification on reliability will also determined.

In chapter 6, the statistical analysis methods reviewed in chapter 4 are assessed theoretically for their applicability to the collected South African transformer failure data.

Chapter 7 presents the results of the data analysis presented in terms of annual average failure rates, failure classification and non parametric analysis methods.

In Chapter 8, the results are discussed with the aim of identifying trends in reliability of transformers with manufacturing periods, and determining whether reliability in South Africa differs significantly from the experiences of other countries (as presented in chapter 2).

The final chapter assesses the validity of the hypothesis and provides recommendations.

CHAPTER 2: TRANSFORMER RELIABILITY

This chapter will provide an overview of transformer reliability as presented in the literature, with emphasis on reliability practices in the industry, definitions and terminology associated with reliability, and statistics from available reliability surveys. Where possible, trends in reliability will be determined with transformer manufacturing period.

2.1. GUIDELINES ON RELIABILITY PRACTICES

The IEEE developed a guide that addresses the collection and reporting of transformer failures by establishing a databases and statistical analysis of data through the calculation of failure rates [IEEE, 1986]. The guide distinguished between reliability improvement and reliability measurement. Determining failure rates was considered as reliability measurement, whereas the classification into failure location and causes should be pursued from a standpoint of reliability improvement.

In 2000, the Cigré study committee on transformers, Study Committee A2, set up a Reliability Advisory Group to consider and recommend how Cigré could and should contribute to activities related to transformer reliability [Lapworth, 2006]. The work of this advisory group has been summarised and recommendations made [Lapworth, 2006]. Recommendations focussed on three areas for future activities, and included (i) reliability of new transformers, (ii) reliability during mid-life, and (iii) risk management at the end of life.

Cigré WG A2.18 gave recommendations on failure identification by developing the following [Cigré WG A2.18, 2003]:

- Standard failure reporting form, which allows for all relevant information to be gathered.
- Failure code, which classifies the failures by the location, the nature of the failure and the cause of the failure
- Failure identity card, which can produce a complete description in a standardised format.

Cigré WG A2.37 (Transformer Reliability) was formed in 2008 and one of its outcomes will be to discuss recommendations to improve the compatibility of the data compiled in different countries and propose a uniform way of collecting, compiling and presenting data [Tenbohlen, 2008].

2.2. RELIABILITY SURVEYS

There is limited literature available in the public domain discussing failure statistics of transformers. Internal surveys are being conducted by certain countries and utilities, and a number of well established databases exist from countries such as Australia, Brazil, Canada, Germany and Japan [Lapworth, 2006]. The results or methodology of these surveys is, however, not made available publicly due to confidentiality and competition between utilities. Another possible reason for the scarce information could be the fact that the industry started referring to the results of the international survey by Bossi [1983] because of its thoroughness, instead of conducting individual surveys.

Measures of reliability from the surveyed literature included the calculation of failure rates, failures classification into failure locations, causes, and modes, and the application of statistical analysis to determine reliability with age. Bossi [1983] presented the results of an international survey of transformer failures from 13 countries that calculated failure rates, and implemented a failures classification. The results of this survey have become an international benchmark in the transformer industry for comparing transformer reliability statistics.

The aforementioned measures of reliability with accompanying definitions of failure were not available in all the surveyed studies. Where definitions were available, they differed between the studies. Definitions from various surveys and international standards are summarised in Appendix A.

Although this is not mentioned in the surveyed studies, cases where the studies were limited to certain measures of reliability, could be due to unavailability of data. Factors influencing the unavailability of data could be:

- With the impact of aging on power system infrastructure, changing economic climate and increased demand for electricity, utilities are forced to invest wisely in new infrastructure. One of the requirements of detailed asset management decisions is sufficient data on the failures history of the installed population. Because most utilities are only now faced with this problem, the need for the collection and record keeping of such data in earlier times may not have been appreciated.
- Lack of skills or time to conduct proper failure analysis to determine failure locations, causes and modes.

2.3. RELIABILITY DEFINITIONS

The most relevant definitions from Appendix A are discussed below.

2.3.1. Failure

The majority of the surveyed studies did not provide failure definitions. In order to have a true comparison between the failure data, it would be required that the failure definitions are similar. This ensures that comparisons are based on failures (events) occurring under the same conditions.

The definition of failure and associated terms, and how they are applied depends on the environment in which it was developed and is being used. The systems operator's focus would be on the impact on the system, ranking failure in terms of system reliability, whereas the plant specialist would rank it in terms of what remedial action would be required to restore equipment functionality [Lapworth, 2006]. A clear example provided by Lapworth [2006] is that of transformers being removed in scheduled outages. The system operator would not consider this as a failure since it would not have an effect on the system reliability, whereas the plant specialist would consider it a failure. Another example is that of insurance companies that could be using insurance claims as a benchmark, where the definition of failure and its severity could be dictated by the value of the claim.

The definitions in IEC [1990] and IEEE [1986] are described as being very broad, whereas Bossi's [1983] definition is more restrictive, in that it considers only problems that require the unit to be removed from service to be repaired [Cigré WG A2.18, 2003]. Further examples of restrictive definitions include those of Kogan [1988] and Higgins [2001]. Despite the difference between having a broader or restrictive definition, both types allow further breakdown of failures into levels of failure severity, or outage type and times.

2.3.2. Reliability

According to the IEEE [1986], stating reliability without mentioning the period of time involved makes it incomplete. Reliability was therefore defined as '*the probability that a transformer will perform its specified function under specified conditions for a specific period of time'*. This definition is in line with that of the IEC [1990] where reliability is defined as *'the ability of an item to perform a required function under given conditions for a given time interval'*.

Cigré WG A2.18 [2003] defined reliability as '*the probability that the equipment will remain in service without a failure occurring'*, excluding the connotation of a specified time interval. According to Cigré WG A2.18 [2003], reliability considerations apply throughout the total life of a transformer.

2.3.3. Failure Rate

Failure rate has been the most utilised measure of reliability because it is based on the count of the number of failures which should be easily obtainable. Where failure rates were available from the available studies, they were calculated and trended by year of failure, and over a period of time (number of years).

International standards claimed that failure rate should only be calculated for forced outages [IEEE, 1986]. Failure rate was calculated as the ratio of the number failures with forced outages of a given population over a given period of time, to the number of accumulated service years for all transformers in that population, over the same period of time. However, if one has defined an event in a specific environment and wants to determine a rate at which the event occurs, there should be no constraint on doing so, if it is defined using mathematically correct terms. The literature has shown various studies determining the rate at which an event (failure) occurs, with the event (failure) being defined based on the environment that it was being used in.

The denominators in the failure rate in IEEE [1986] and Bossi [1983] are the same, although they are phrased differently, and would yield the same results if failures only in forced outages were considered, as per the IEEE definition. Kachler [2001] proposed that the failure rate definition of the IEEE [1986] should be calculated over a 10 year floating time period.

The IEEE transformer committee developed a failure rate evaluation rating, which was not entered into the IEEE standard of 1986 [Kachler, 2001]. According to this evaluation scheme, Table 1 failure rates can vary from being excellent to unacceptable. This evaluation scheme appears to be centred on the 2% failure rate determined by Bossi [1983], where failure rates above 2% are considered as unacceptable.

Table 1: Proposed failure rate evaluation scheme developed by the IEEE [Kachler, 2001]

FAILURE RATE	EVALUATION
FR ≤ 0.5%	Excellent
0.5% < FR ≤ 1%	Good
1.0% < FR ≤ 1.5%	Satisfactory
1.5% < FR ≤ 2%	Acceptable
FR > 2%	Not Accepted

2.4. AVAILABLE RELIABILITY STATISTICS

Measures of reliability included the calculation of failure rates, the classification of failures into failure location, causes and modes, and determining reliability with age. The most significant results and constraints are discussed below.

2.4.1. Constraints

Without clear definitions, as well as adequate descriptions of the transformer application, voltage level, failure period and manufacturing period, making comparisons to identify trends becomes difficult. Most of the surveyed literature adhered to this constraint. In summary, the following factors constrained the comparison of the available statistics:

1. Limited publicly available reliability survey results.

2. The majority of the surveyed studies did not provide failure definitions. In order to have a true comparison between the failure data, it would be required that the failure definitions are similar. This ensures that comparisons are based on failures (events) occurring under the same conditions.

3. Where failure rates were given, the majority of the sources did not provide the formula used for calculating failure rate.

4. Further, the majority of the studies did not provide the manufacturing period of the failed units. In most cases only the failure period was given, and an attempt was made to determine the manufacturing period from the failure period. However, this introduced another constraint. For example, if the failure period was from 2000 to 2005, then the manufacturing period would be pre 2005, meaning that this could include older and younger

units, i.e. pre and post 1980. If the spread of the older versus younger units is not known, it becomes difficult to assess which group's failures actually dominated the sample or if they had equal contributions. The same reasoning applies to the failures classification per manufacturing period, where a specific failure location cause or mode could dominate a sample.

5. The surveyed studies are from different countries with varying transformer design specifications, maintenance philosophies, condition monitoring practices and operating conditions. These factors could have an impact on outcomes of comparisons, however the extent to how much these factors' impact affects the results of the surveys is not known.

6. The surveyed studies did not use the same categorisation of transformers according to application. Bossi [1983] referred to power station, substation and autotransformers, whereas others referred to GSU, transmission and distribution transformers. Although this is not mentioned in Bossi [1983], power station transformers include GSUs, and station and unit transformers. Station transformers are used to supply auxiliary equipment in the power station, and unit transformers' primary winding is directly connected to the generator output [Kulkarni, 2004]. In most cases, the difference between these units is the highest system voltage each connects to. In the case of units housed in substations, higher voltage units are more generally referred to as transmission units, and the lower voltages referred to as distribution units. Transmission and distribution transformers are housed in substations, and they are therefore also substation transformers. Transmission and distribution transformers can also be two winding, three winding or autotransformers.

7. In the surveyed studies, the classification of failures was done according to failed location, failure cause or failure mode. Some of the surveys contained data with mixed classification where failure causes, and/or failure locations, and/or failure modes were used together [Sokolov, 2005-1, 2005-3, Doble Engineering, 2006]. This suggests that there is not consensus in the industry regarding the use and application of failure classification terminology.

The abovementioned constraints were acknowledged, and attempts at comparisons have therefore been made with caution.

2.4.2. Failure Rates

Bossi [1983] investigated more than 1000 failures from 13 countries, in transformers not older than 20 years, and failing in the period 1968 to 1978. This was a very comprehensive study where failure rates were calculated in terms of transformer application, voltage level, and outage type. Forced outages and the combination of forced and scheduled outages were considered.

The study concluded that: 'For the units installed on systems operating at voltages lower than 700kV, the average failure rate may be stated as 2%.' The 2% derivation did not distinguish between outage types. Since then, this statistic has become an international benchmark in the transformer industry for transformer failure rate performance. Considering the failure period, the year of manufacture of these units would be up to and including 1978. This would make the failure rate of 2% inapplicable to transformers manufactured after this period. Bossi [1983] also concluded that failure rates increase with increasing voltage level.

The failure rates from the manufacturing industry were given in Kachler [2001]. The in-service failure rates from the Siemens transformer manufacturer over the ten year period from 1990 to 1999, and thus with manufacturing period up to 1999, is shown in Table 2. The failure rates are all within the 2% benchmark, and based on the proposed evaluation in Table 1, the combined failure rate of all the factories at 0.12% is excellent over the 10 year period.

Results from China of transformers manufactured up to 1998 in Table 3, show failure rates of different power transformer manufacturers and vary from being excellent to unacceptable.

Table 2: Failure rates from all Siemens power transformer factories for the period 1990 to 1999 [Kachler, 2001]

SIEMENS FACTORIES	N = NO. OF DELIVERED UNITS	SY = NO. OF SERVICE YEARS	Nf = NO. OF FAILED UNITS	FAILURE RATE (%) = (Nf/SY).100
A	168	1274	1	0.08%
B	268	1240	1	0.08%
C	464	2379	1	0.04%
D	463	2425	4	0.16%
E	109	169	1	0.59%
F	371	1490	2	0.13%
G	836	4140	10	0.24%
H	3717	16787	17	0.10%
Total	6396	29904	37	0.12%

Table 3: 1998 In-service failure rates for 220kV to 500kV transformers in China [Kachler, 2001]

MANUFACTURER	FAILURE RATE (%)
Siemens	0.14
Xiang Transformer	0.47
Hitachi	0.50
ABB	0.56 - 1.50
GEC Alstom	0.67
Shenyang Ltd.	0.78
Saporozhye, Russia	1.00
Elin	1.50
Mitsubishi	3.00

The failure rates of variously rated transformers from utilities in different countries spanning from 1968 to 2005 is shown in Table 4. With the exception of Bossi [1983] and Fleeman [2002], none of the sources in Table 4 provided definitions of failure or formulas for failure rate calculation. The failure rate calculations of Bossi [1983] and Fleeman [2002] were based on the same formula.

Failure rates per annum across different manufacturing periods spanning from pre 1978 to pre 2005 varied, but remained within the 2% benchmark, assuming the failure rate calculations have been based on Bossi [1983]. At 2.9%, only the failure rate of 765kV pre 1986 manufactured GSUs exceeded the 2% industry benchmark. In a way, this result could have been expected since the 2% failure rate was based on units up to 700kV, and therefore excludes the 765kV units. This could suggest that the 2% failure rate determined by Bossi [1983] was valid across all manufacturing periods.

Only two studies showed clear distinctions between the failure rates according to manufacturing period, and both applied to single phase GSUs. The outcomes of the surveys contradict each other: Kogan [1988] reported that the older designs (post 1977) were more reliable than later versions, whereas Hall [2006] reported that failure rates made older designs (pre 1974) less reliable than their younger counterparts.

Kogan [1988], Wagenaar [1994], and Fleeman [2002] considered 345kV and 765kV GSU and autotransformers in the United States, which were manufactured pre and post 1977, and pre and post 1986. In the initial study, Kogan [1988] observed that post 1977 manufactured 765kV units had higher failure rates than their pre 1977 counterparts. The lower failure rates of pre 1977 units have been attributed to the fact that manufacturers built more margins into the designs, by testing units at higher lightning and induced test levels than required by the specification. In light of the higher failure rates, an initiative was undertaken to improve dielectric specification of these transformers and this was enforced in 1986 [Wagenaar, 1994, Fleeman, 2002]. Since then, studies have shown lower failure rates in post 1986 manufactured units, compared to pre 1986, which varied from 1.3% to 2.9% before the implementation of the new specification [Fleeman, 2002].

In a study of the reliability of single phase generator transformer sets in the United Kingdom, the failure rate for units failing in the period 1974 to 1994, post 1974 build, was reported to be 1.2% [Hall, 2006]. This was an improvement in failure rate which stemmed from initiatives in terms of specification, design and manufacture, to enhance the reliability of the transformer fleet, after the poor experience with three phase units during 1966 to 1974, the pre 1974 build. Since 1995, the failure rate of single phase transformers has shown further improvement to 0.6%.

This demonstrates that changes in the specification allowed differences between manufacturing periods to be observed in the failure rate. Although these two studies are not sufficient to draw a thorough assessment of reliability, they could suggest significance in behaviour of transformers prior to and after the 1970’s, and transformer application.

Where failure rate by year of failure was determined, two opposing scenarios also resulted. Bossi [1983] showed an increasing failure rate by year from the late 1960’s up to 1978 (Figure 1), and, in a study covering 1966-88, Hall [2006] showed a decreasing failure rate after improvements in the design and specification of transformers (Figure 2 and Figure 3).

Bossi [1983] indicated an increase with time that is more pronounced during the years 1974 to 1977 in the range 100kV to 300kV, and autotransformers in the range 300kV to 700kV. The failure rate of GSUs in the United Kingdom was based on a 5 year average and shows a decrease from the 1970's (Figure 2 and Figure 3).

Table 4: Failure rates from surveys from 1968 to 2005

SURVEY	APPLICATION/ CLASSIFICATION	FAILURE PERIOD	MANUFACTURING PERIOD	FAILURE RATE (%)	SOURCE
Cigré International Survey	All voltage levels (60kV-700kV)	1968 - 1978	Pre 1978	2	[Bossi, 1983]
United Kingdom	All voltage levels	Pre 1987	Pre 1987	< 2	[Allan, 1987]
United Kingdom	Generator Step-Up, Major failures	1974 - 1995	Pre 1995*	1.2	[Hall, 2006]
ZTZ Service Database, Ukraine	Generator Step-Up & Transmission Rated power $\geq$ 100MVA,	2000 - 2005	Pre 2005	1 - 2	[Sokolov, 2005-2]
US-NGRID, United States	Distribution 115kV, 69kV & <69kV	-	-	0.35 - 0.8	[Prout , 2003]
Hydro Quebec, Canada	All voltage categories, major failures	-	-	< 0.5	[Foata, 2006-1]
American Electric Power	345kV & 765kV	Pre 1986	Pre 1986 *	1.3 - 2.9	[Fleeman, 2002]
American Electric Power	345kV & 765kV	Post 1986	Post 1986 *	0.35 - 1.35	[Fleeman, 2002]
Australia & New Zealand	Costly failures	Pre 1996	Pre 1996	0.4	[Austin, 2001]
* Indicates studies where the manufacturing period was given.					

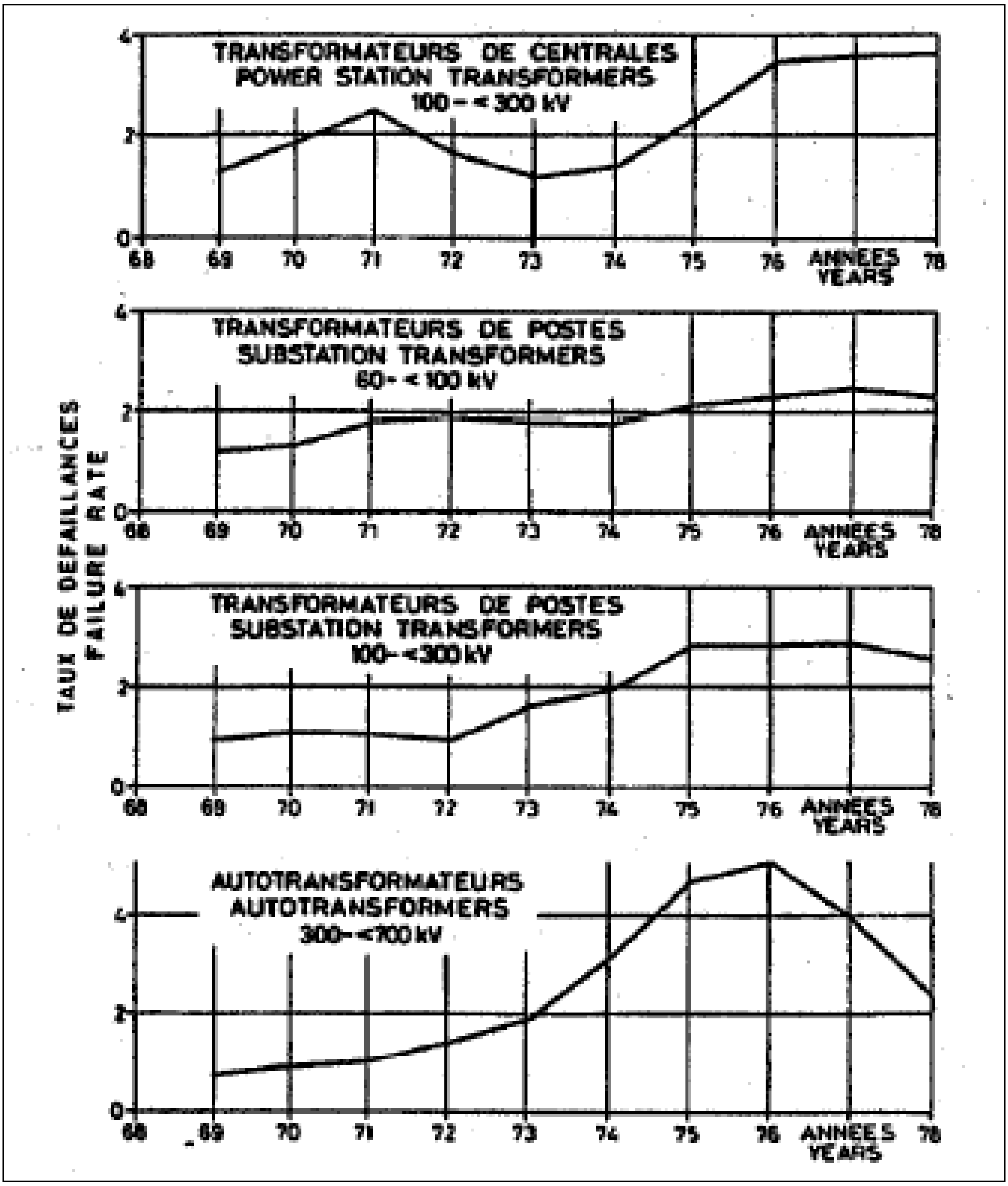


Figure 1: Yearly failure rates according to application and highest winding voltage [Bossi, 1983]

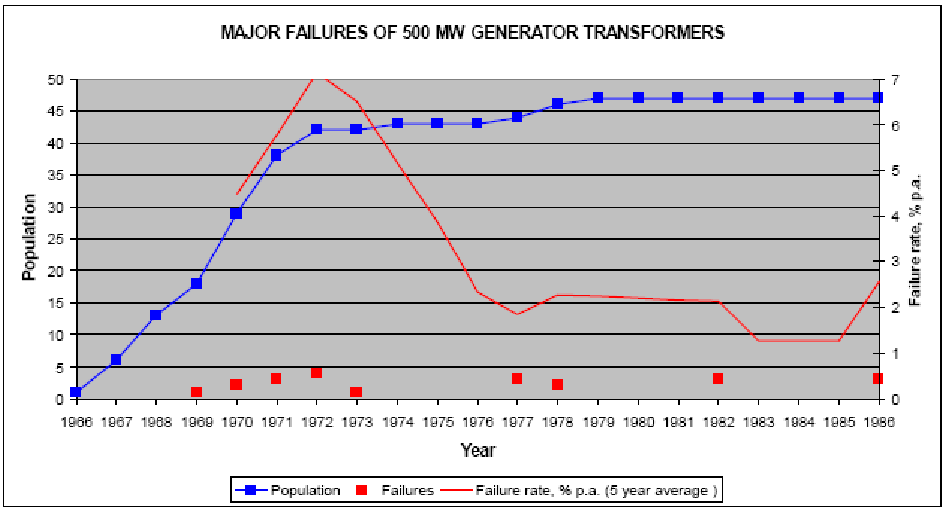


Figure 2: Major failures of 500MW generator transformers in the United Kingdom over the period 1966 to 1986 [Hall, 2006]

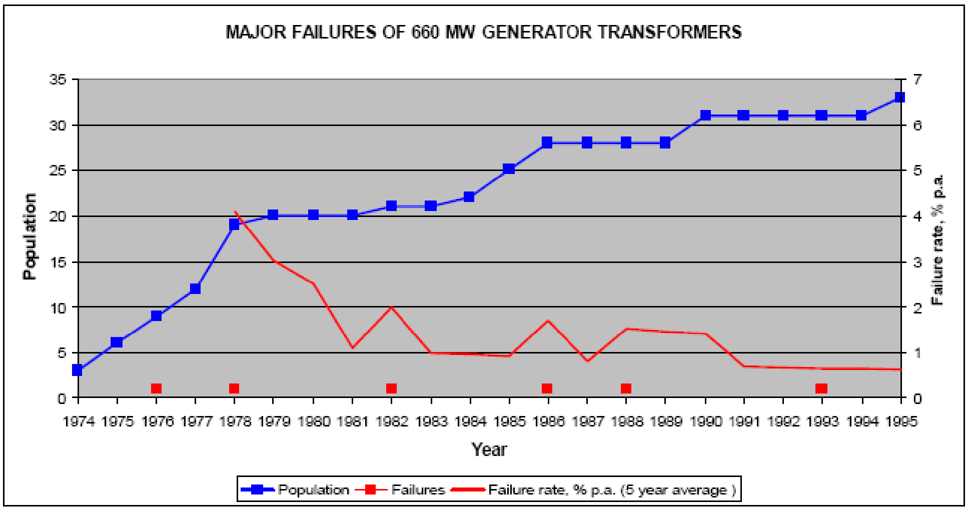


Figure 3: Major failures of 600MW generator transformers in the United Kingdom over the period 1974 to 1995 [Hall, 2006]

2.4.3. Reliability with Age

The reliability with age was evaluated by determining failure rate and failure probability by age for groups of transformers, or per failed component of the transformer.

Two types of failure rate have been mentioned: a failure rate for a group of transformers over a time period, and a time dependent failure rate given by the hazard function. Bossi [1983] determined the failure rate by age group, and applied the same failure rate calculation as used for a group of transformers. Later references used the hazard function for determining the failure rate with age [Sokolov, 2005-1, 2005-2, Foata, 2006-2, Kogan, 1988, Prout, 2003]. The failure probability with age was determined from the cumulative distribution function and the probability density function.

According to Lapworth [2006], although determining the reliability with age statistical analysis techniques (hazard function, probability density function, and survival function) provides a more realistic model, it is debatable how relevant a statistical evaluation of transformer failures will be, since they are so dependent on random external events and internal weaknesses. Lapworth [2006] further argues that a more useful approach would be to determine the likely onset of reliability on an individual basis.

Results from surveyed literature are discussed below.

Analysis of the failure rate with age over the period 1955 to 1977 in the former USSR, indicated a high early life failure rate which was more pronounced in the pre 1965 build (Figure 4) [Sokolov, 2005-2]. Improvements in design have since caused the failure rate to increase with age [Sokolov, 2005-1].

Further analysis of pre 2005 manufactured autotransformers and GSUs from CIS countries, in the voltage range 220kV to 500kV, failing in the period 1963 to 2005, indicated that failure rates tended to decrease with age; higher early life failure rates were more pronounced in the period 0 to 3 years (Figure 5). The rise in failure rate in the age group 7 to 15 years has been attributed to the weak designs of bushings and tap changers, dielectric degradation of winding insulation and mechanical movement of windings. Failures after 25 years have also been associated with bushings and on-load tap changers of a certain design and dielectric degradation of insulation. In the age group between 35 and 40 years, failures were associated with wear-in, random failures and wear out of weak components.

Pre 1978 manufactured transformers failures showed variation with voltage groups. The failure rate decreased with age in the 60kV to 100kV voltage group, and increased with age in the higher voltage ranges from 100kV (Table 5).

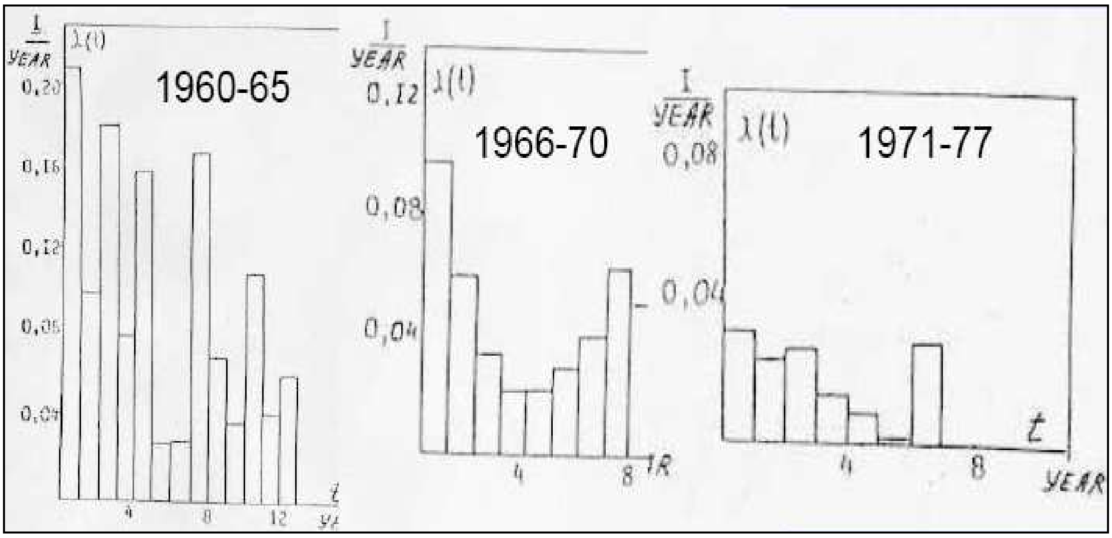
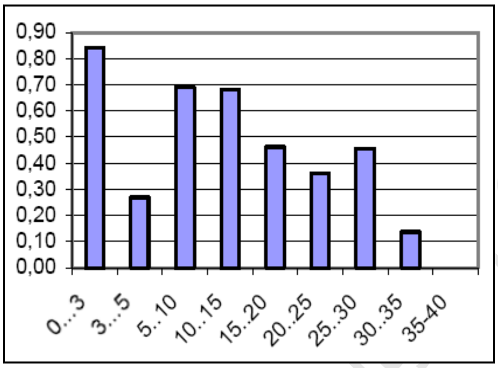


Figure 4: Failure rate with age for transformers in the former USSR [Sokolov, 2005-2]



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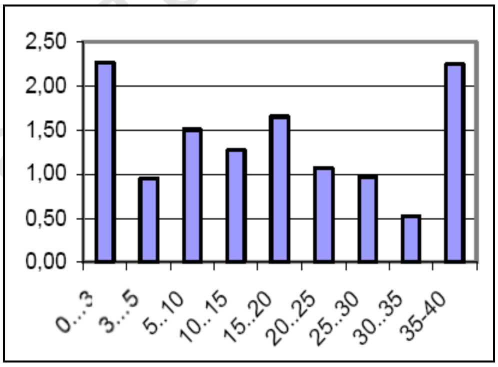

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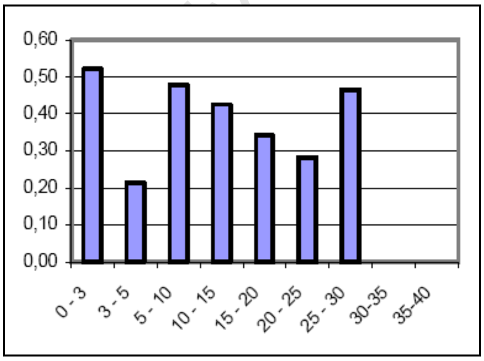
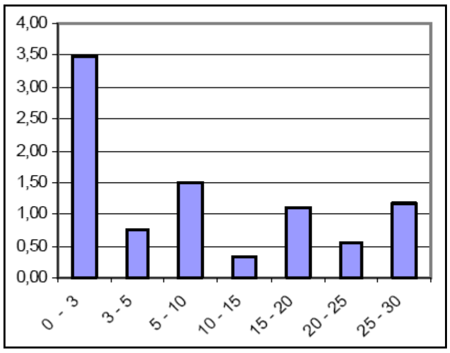


(c)



(d)

Figure 5: Failure rate with age group over the period 1963 to 2005 for (a) autotransformers 220/110kV, (b) autotransformers 300/110kV, (c) autotransformers 500/220kV, and (d) GSUs 400MVA, 330kV [Sokolov, 2005-1]

Table 5: Failure rate with age groups of transformers manufactured up to 1978 [Bossi, 1983]

Age Groups	**60 ≤ kV < 100**		**100 ≤ kV < 300**		**300 ≤ kV < 700**	
	Failures	**Failure Rate (%)**	**Failures**	**Failure Rate (%)**	**Failures**	**Failure Rate (%)**
0 ≤ Age ≤ 5	96	2.8	131	1.7	56	1.9
5 < Age ≤ 10	80	2.1	143	1.9	52	2.5
10 < Age ≤ 20	146	1.7	216	2.2	40	3.2

In 1986, the AEP Service Corporation in the US conducted an analysis of the time dependent failure rate of 345kV and 765kV autotransformers and GSUs manufactured before and after 1977 [Kogan, 1988]. A higher early life failure rate was observed in the 765kV units manufactured after 1977 compared with those before this period, as shown in Figure 6. The lower failure rates of pre 1977 units have been attributed to the fact that manufacturers built more margins into the designs, by testing units at higher lightning and induced test levels than required by the specification.

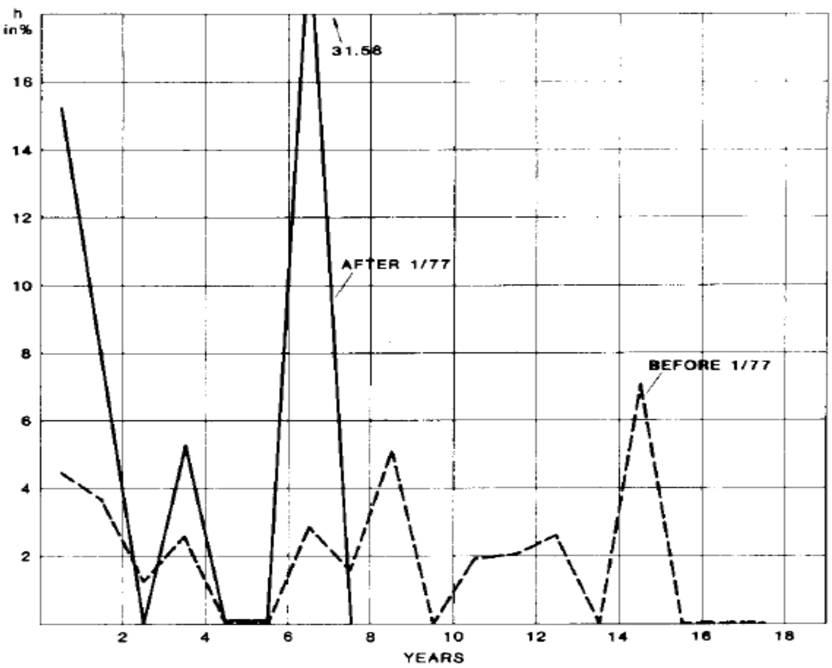


Figure 6: Hazard function of 765kV transformers manufactured before (broken line) and after 1977 (solid line) [Kogan, 1988]

Statistical life analysis of two groups of transformers from the Netherlands, with year of manufacture spanning from 1950 to 2007 has been studied [Jongen, 2007] Most of the failures have been attributed to aging mechanisms in the transformer. Estimations of the cumulative distribution function and hazard function for 150kV and 110kV (group 1), and 50kV (group 2) transformers are shown in Figure 7 to Figure 11.

Both groups indicated an increasing failure probability and failure rate with age, as shown in Figure 7 and Figure 8. The onset of failure is before 17 years for the group 1 transformers, while in group 2 transformers, the onset was at an earlier age. Ten percent of the group 1 units failed by the age of 33, and group 2 units by 35 years. Mean lives of groups 1 and 2 units were 49 and 71 years, respectively.

Analysis by failed component was also conducted for tap changer and winding related failures, as shown in Figure 9 to Figure 11. Group 1 transformers were only analysed in terms of tap changer related failures, in which 10% failed by 37 years, and half by 64. Both tap changer and winding related failures were analysed for group 2 transformers, where the mean life was 96 and 75 years respectively. Ten percent failed by the age of 43 and 52 years, in tap changer and winding related failures, respectively.

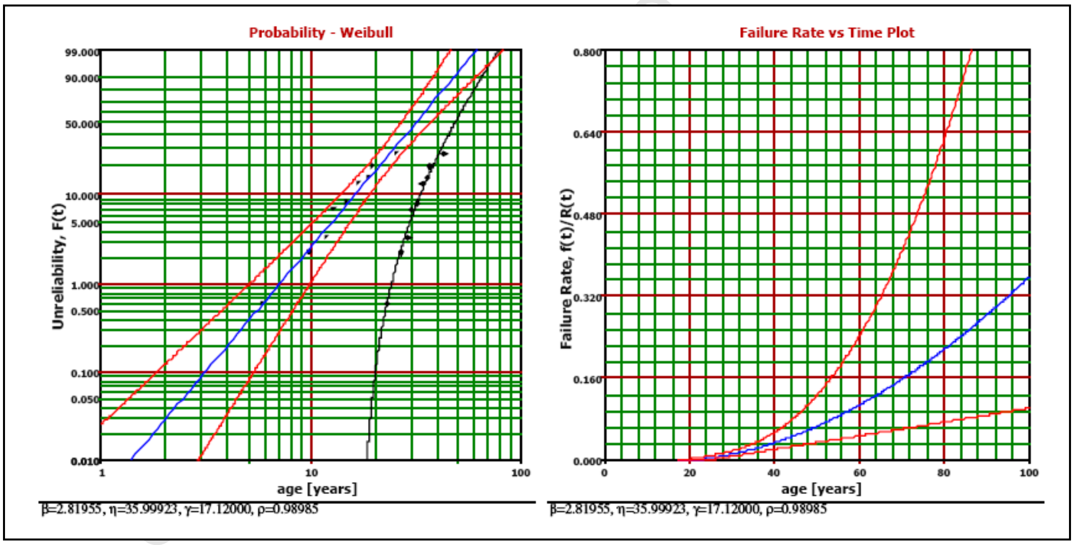


Figure 7: Cumulative distribution function and hazard function for transformers with primary voltage 150kV and 110kV [Jongen, 2007]

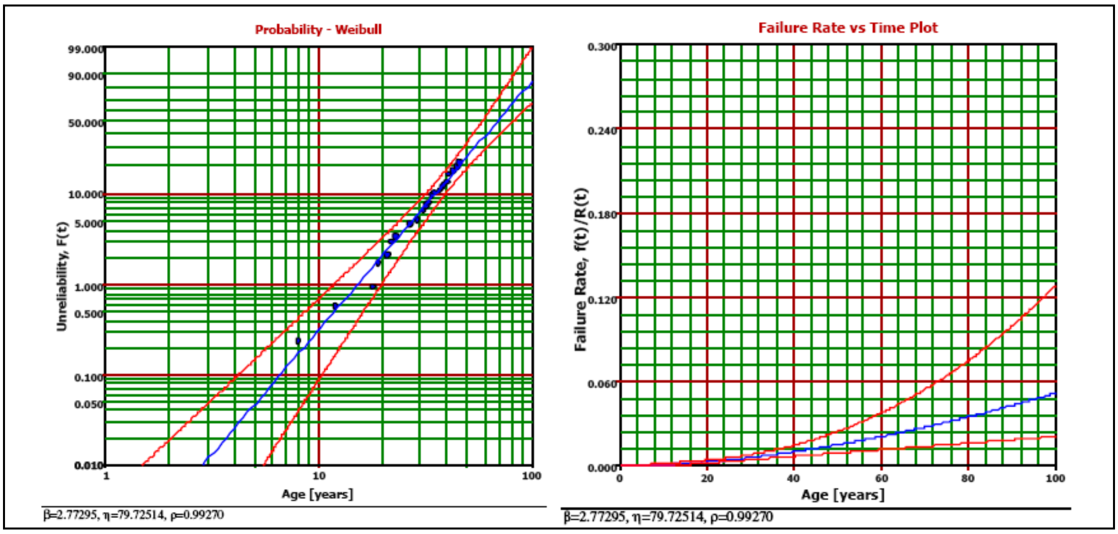


Figure 8: Cumulative distribution function and hazard function for transformers with primary voltage 50kV [Jongen, 2007]

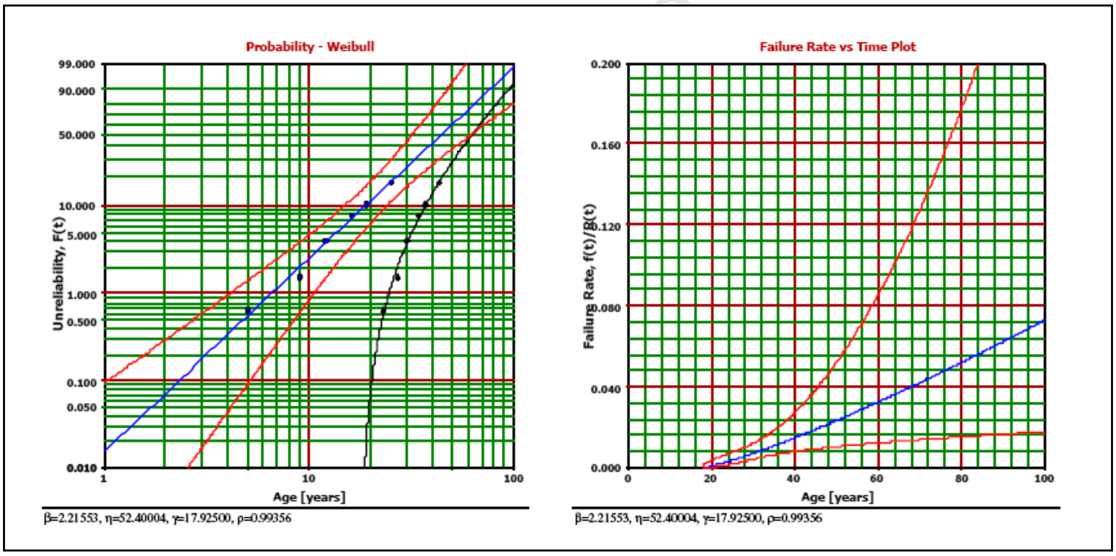


Figure 9: Cumulative distribution function and hazard function for tap changer related failures in 150kV and 110kV transformers [Jongen, 2007]

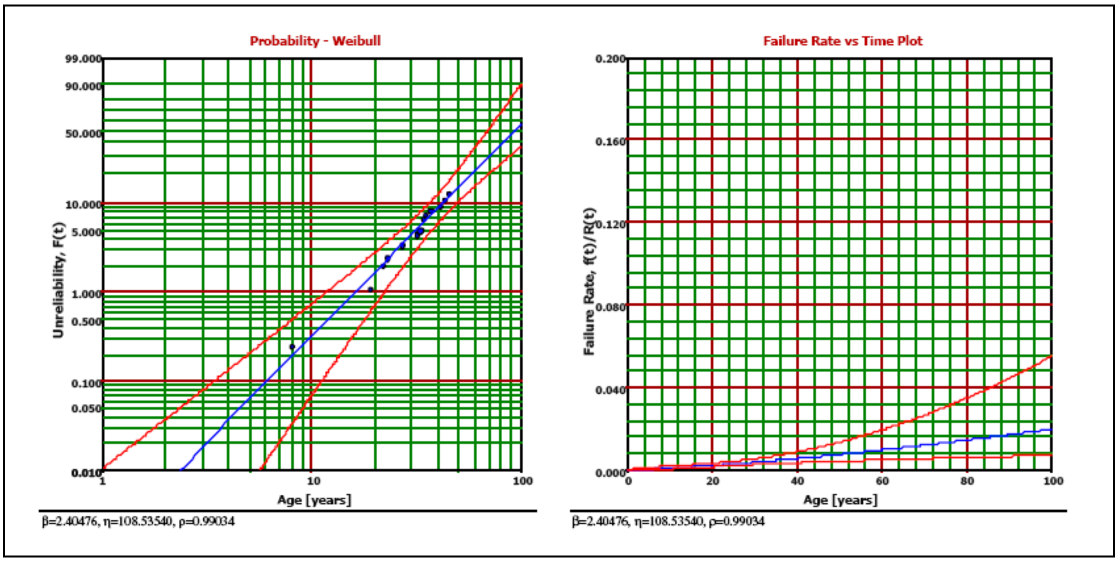


Figure 10: Cumulative distribution function and hazard function for tap changer related failures in 50kV transformers [Jongen, 2007]

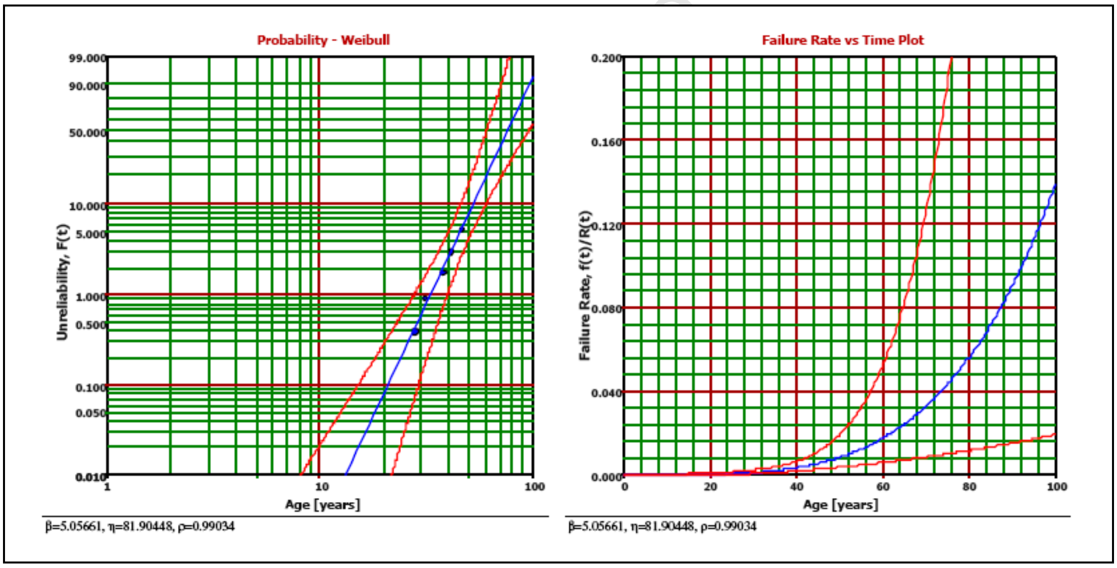
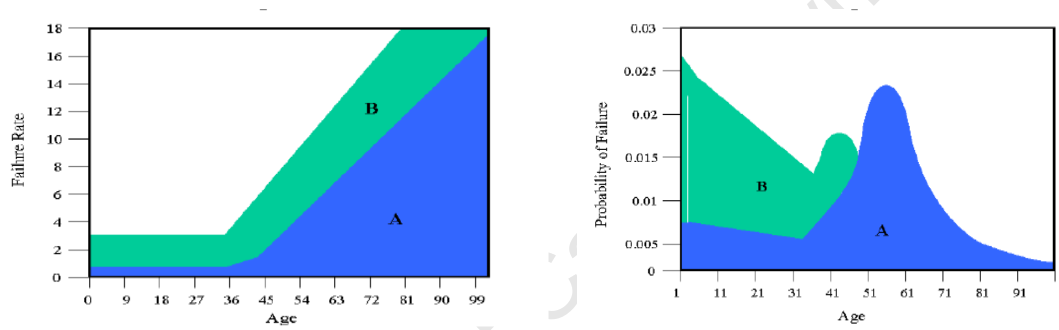


Figure 11: Cumulative distribution function and hazard function for winding related failures in 50kV transformers [Jongen, 2007]

Two design families of 275kV and 400kV transformers from UK National Grid were compared using the hazard function and probability density functions (Figure 12) [Prout, 2003]. No failure period or manufacturing periods were provided in the study.

Early life failures were omitted from the hazard functions and they show only the normal life and wear out periods. Family 'A' had lower normal life failure rates during the first 35 years, and was followed by end of life failures due to normal paper aging, as shown in Figure 12a. The probability density function in Figure 12b of ‘A’ further showed well designed units, as can be observed from lower failure probabilities in early life. Family ‘B’ on the other hand had weakness in early life, where failure rates were about 5 times higher than those of family ‘A’.

Most failure surveys have indicated tap changer related failures to be among the major contributors. A study of on-load tap changer reliability over the period 2003 to 2005, on a population of 1179 on-load tap changer units, revealed an increasing failure rate with age [Foata, 2006-2].



(a) (b)

Figure 12: Two transformer design families (a) Hazard function and (b) Probability density function [Prout, 2003]

2.4.4. Failure Locations

Winding and terminal related failures were the largest contributors in failure rates of power station transformers manufactured up to 1978 [Bossi, 1983]. A breakdown in terms of transformer application type at the power station was not made.

GSU failure statistics of units manufactured up to 2005 were largely winding related, where failures developed in the winding minor insulation [Sokolov, 2005-1]. A further breakdown of power station transformers in terms of application, over the failure period 2000 to 2005, indicate tap changer related failures were more prominent in auxiliary transformers, and dielectric type failures associated with the winding minor insulation and major insulation in start-up transformers.

Contributions to failure from the tap changer were most prominent in post 1974 manufactured GSUs in the United Kingdom [Hall, 2006].

In pre 1978 manufactured substation transformers with an on-load tap changer, the tap changer was the major contributor followed by winding related failures [Bossi, 1983]. In units without an on-load tap changer, failure of the windings, and the tank and dielectric fluid were most prominent. In autotransformers, windings and other accessories dominated.

The failures of pre 2005 manufactured transmission transformers above 100MVA occurred mostly in the bushings and major insulation [Sokolov, 2005-1]. The evaluation of a group of 167MVA transformers, also manufactured pre 2005, showed a similar distribution, with the inclusion of minor insulation and winding insulation failures [Sokolov, 2005-1].

In lower voltage transformers up to 69kV manufactured up to 1985, from the Doble database, winding related failures contribute to most of the failures [Prout, 2003].

The US-NGRID study is an example of mixed classification where failure locations and causes have been combined, and referred to as failure causes. The study shows smaller contributions from the tap changer and bushings in units manufactured up to 2003, which only occurred in the 115kV range and in units below 69kV.

The EPRI study of units in the range 69kV to 161kV indicates more tap changer related failures in distribution units manufactured up to 2000, followed by windings and bushings [Bhavin, 2007].

Statistics from the Netherlands for pre 2007 transformers, show tap changer related failures dominated in units with the highest winding voltage 50kV to 150kV [Jongen, 2007].

Core related failures did not feature as a major contributor in any of the surveyed studies, and was a minor contributor in pre 1978 manufactured transformers, irrespective of transformer application [Bossi, 1983].

2.4.5. Failure Causes

According to Sokolov [2005-1], three main causes of failure may be considered where failure occurs when the withstand strength of the transformer with respect to one of its key properties is exceeded by operating stresses. These are:

- Originally insufficient safety margin due to underestimation operational stresses (poor specification), design deficiencies, manufacturing weaknesses, or material defects.

- Operation stresses exceed specified quantities (unusual event, operational error).
- Critical deterioration of safety margin, including inadequate maintenance, low quality repair or refurbishment. With years, one can expect gain in weight of this third cause, which automatically increases the influence of initial design margin, as well as operational stresses.

From a manufacturer's perspective, similar views are shared where transformer failures can be grouped under three main headings, as shown by Allan [1995]:

- Failures due to weak specification, design deficiencies, manufacturing weaknesses or material defects,
- Failures due to system disturbances, operational factors, or interactions between the transformers and other equipment on the system,
- Failures which result from maintenance operations, repairs or refurbishment that has or have not been undertaken.

Pre 1978 manufactured units, in all three groups of transformer application, failed mostly due to design and manufacture related problems [Bossi, 1983].

The EPRI study of distribution units manufactured up to 2000 and in the range 69kV to 161kV showed that manufacturing and inadequate short circuit strength ranked the highest [Bhavin, 2007].

In the US-NGrid study of transformers up to 345kV manufactured up to 2003, system through-faults are the largest contributor, followed by design and manufacturing related problems [Prout, 2003].

Apart from 'other' causes, failures in a US survey were mostly due to external corrosion and aging. In CIS countries, contamination, short circuits and oil barrier insulation problems were most prominent [Allan, 1995]; this is also another example of mixed classification. No manufacturing or failure period was given for the two studies.

Data from two insurance companies in the United States across different industries of application, Hartford Steam Boiler and Marsh insurance companies, indicate electrical disturbances, and winding and connections failures as the largest contributors, respectively

[Doble Engineering, 2006]. The results also contain a mixed classification of failure causes and locations, based on units manufactured up to 1999.

Not many of the literature sources provided a breakdown of failure causes with failure locations. According Sokolov [1997], approximately 80% of bushing failures in the period 1986 to 1996 (the pre 1986 build) occurred after 10 to 12 years in service, where design deficiencies and aging were typically involved.

2.4.6. Failure Modes

In Bossi [1983], failure origin is equivalent to that of failure mode. For the pre 1978 transformers, dielectric mode failures were more prominent in units with an on-load tap changer in the group of power station and autotransformers, and mechanical in substation units, for the combination of forced and scheduled outages. When considering units without an on-load tap changer, the results are significantly different, with mechanical and dielectric mode failures most prominent in power station and autotransformers, and substation units, respectively.

The ZTZ Service database considered 108 major failures of units from 9 different manufacturers rated 100MVA and above, all manufactured up to 2005 [Sokolov, 2005-1]. Most GSUs (of which 56% were manufactured after 1975) failed due to dielectric mode failures originating in the windings insulation. According to Sokolov [2005-1], thermal mode failures have shown an increasing trend where they resulted in overheating of leads and connections.

Failure statistics from the Doble database presented in Sokolov [2005-1], were based on 52 major failures above 100MVA, of which 57% were manufactured after 1971. No distinction was made between application types but most of the failures were due to dielectric type failures [Sokolov, 2005-1].

Kogan [1988] reported increased dielectric mode failures in GSU and autotransformers in the range 345kV to 765kV, in the absence of any system disturbances such as lightning, elevated system voltage, line or switching faults, all of which were manufactured after 1977. In 765/345kV autotransformers problems were nearly all caused by dielectric failure, and mainly concentrated in the first nine years of life. Failures at later ages were of the mechanical type.

2.5. SUMMARY

The measures of reliability as used and determined by the industry have been identified and discussed. In summary, two of the research questions could be addressed in this chapter:

- How, and to what extent, can reliability be determined from the available failure data?
- What trends can be observed between the reliability (or failure) of transformers from different manufacturing periods?

These questions are addressed and additional aspects, raised below.

2.5.1. Determining Reliability from Failure Data

International standards and guidelines have been used to provide the transformer industry with recommendations on how to treat failure data for the purpose of assessing reliability. These recommendations addressed definitions associated with reliability, the collection and gathering of data, and classification of failures and application of statistical analysis. The statistical analysis included calculation of failure rates, and determining the hazard function, probability density function, cumulative distribution function and survival function.

From the limited available literature on transformer reliability surveys, the sources appeared to apply industry recommendations to some extent, but there were limitations to determining all the measures of reliability. The unavailability of data was considered as a possible contributor to the limitation.

2.5.2. Trends in Reliability According to Manufacturing Periods

There is limited literature available in the public domain discussing failure statistics of transformers. Very little and only scattered insight was gained into reliability according to manufacturing periods due to constraints discussed in section 2.4.1.

2.5.2.1. Industry Benchmark for Failure Rate

The results of the international survey in Bossi [1983] appeared to provide the most reliable statistic giving the performance of the pre 1978 build, and has become an international benchmark in the transformer industry for comparing transformer reliability, and, in particular, the failure rate.

Apart from the failure rate of 765kV pre 1986 manufactured GSUs, the failure rates per annum across different manufacturing periods varied but remained within the 2% benchmark. This could suggest that the 2% failure rate determined in Bossi [1983] could be valid across all manufacturing periods, and all transformer applications up to 700kV.

2.5.2.2. Failure Rate Significance with Voltage Level

Bossi [1983] indicated that the failure rate of pre 1978 manufactured transformers increased with increasing voltage level. Pre 1978 manufactured transformers also showed variation with voltage groups in the failure rate with age, where it decreased with age in the lower voltage group, and increased in the higher voltage group.

The performance of pre 2007 manufactured transformers in Jongen [2007] agreed with the observation for transformers above 100kV. According to Solokov [2005-1], the record of pre 2005 manufactured transformers in the same voltage group did not agree with Bossi's and Jongen's observation.

2.5.2.3. Failure Rate Significance with Age

Prout [2003] indicated an increasing failure rate with age when comparing two design families.

Sokolov [2005-2] indicated a decreasing failure rate with age in pre 1965 manufactured transformers, which after design improvements, led to an increasing failure trend with age [Sokolov, 2005-1].

Three studies further showed significance with voltage level. The failure rate of pre 1978 manufactured units in the higher voltage ranges above 100kV tended to increase with age and those below 100kV decreased with age [Bossi, 1983]. The failure rate of pre 2005 manufactured GSUs from 220kV decreased with age [Sokolov, 2005-1]. Jongen [2007] indicated an increasing failure rate with age for units from 50kV to 150kV.

Tap changer and winding related failures also indicated an increasing failure rate with age [Foata, 2006-2, Jongen, 2007].

2.5.2.4. Failures Classification According to Manufacturing Periods

Transformer failures were classified into failure location, causes and modes. Apart from Sokolov [1997], none of the sources provided a breakdown of failure causes per failure location.

Failure Locations: Despite the varying results from the surveyed studies, winding related failures featured as one of the major contributors, irrespective of transformer application and manufacturing period. GSUs appeared to be more prone to winding related failures, while substation transformers also featured tap changer or bushings related failures, irrespective of manufacturing period. Core related failures did not feature as a major contributor in any of the surveyed studies.

Failure Causes: Design and manufacturing related problems were identified as major contributors in most of the surveyed studies, irrespective of manufacturing period and transformer application [Bossi, 1983, Prout, 2003, Bhavin, 2007].

Failure Modes: Dielectric mode failures featured as major contributors in most of the surveyed studies, irrespective of manufacturing period and transformer application [Bossi, 1983, Kogan, 1988, Sokolov, 2005-1, Doble Engineering, 2006]

This suggests that there has been no significant change with manufacturing period in the major contributors of failure, or that, with reference to constraint number 4 discussed in section 2.4.1, the dominance of a contributor of failure in a particular manufacturing period is being observed.

2.5.3. Impact of Design Specification on Reliability

Studies which indicated clear distinctions of transformer reliability according to manufacturing periods were all related to improvements in the transformer design specification [Kogan, 1988, Sokolov, 2005-1, Hall, 2006].

2.5.4. Application of Statistical Analysis

Two main types of failure rate have been identified; a failure rate for a group of transformers over a time period, and a time (age) dependent failure rate given by the hazard function. The trends according to manufacturing period were summarised in section 2.5.2.3.

Other statistical analysis methods used in the available surveys included determining the failure probability with age from the probability density function, and the cumulative distribution function. Lapworth [2006] questioned the relevance of statistical analysis techniques to transformer failures since they are so dependent on random external events and internal weaknesses.

2.5.5. Next Steps

Based on the summaries in sections 2.5.1 to 2.5.4, the following aspects/ (research questions) still need to be addressed:

1. Identifying the changes in transformer design, manufacturing and technology, and determining to what extent periods can be defined that could have had an impact on transformer reliability.
2. Identifying whether changes in the specification of transformers in South Africa had an impact on reliability.
3. Reviewing the theory behind the statistical analysis measures with emphasis on their applicability/relevance to transformers.
4. Recommendations from international standards and guidelines on the treatment of failure data should be applied to transformer failures in South Africa.
5. Through the classification of failures and application of statistical analysis methods, the analysis of the South African data should address the following:
    - What trends can be observed between the reliability (or failure) of transformers from different manufacturing periods?
    - Are there differences in the experience of transformer reliability according to manufacturing periods between South Africa and other countries?
    - How did changes in specification impact transformer reliability?
6. Are older designs more reliable than newer designs?

CHAPTER 3: DEVELOPMENTS IN TRANSFORMER DESIGN, MANUFACTURING AND TECHNOLOGY

This chapter investigates the developments in design, manufacturing and technology which might have affected transformer reliability, based on the failure statistics discussed in chapter 2. Developments in the specification of transformers in South Africa are also discussed.

3.1. CONSTRAINTS

The developments were not documented in great detail in the surveyed literature. Furthermore, not all the sources gave an indication of the design period as a calendar year (e.g. 1950's) consistently throughout the paper. In some cases a period of time (e.g. 20 years ago) was referred to. In order to relate this to a calendar year, where possible, the year of the publication was subtracted from the period of time given in years. In other studies, where no periods were given, the developments were mentioned for completeness' sake.

3.2. DEVELOPMENTS IN TECHNOLOGY

The first transformer was built in 1885 [Allan, 1991], and the basic principles of modern transformer design laid down in the 1920's and 1930's [Heathcote, 1998]. Since then, the basic sub-systems and design features of a transformer have remained unchanged.

In the last few decades (approximately since the 1980's, based on the publication date of the paper), transformer technology development has focussed on operation, maintenance, and the necessary tools and equipment for condition monitoring and diagnosis [Baehr, 2001].

3.2.1. Core Material

The development of core material was aimed at reducing core losses, through the use of improved and thinner grades of core steel [Kulkarni, 2004], and is illustrated in Figure 13.

Cold rolled grain oriented manufacturing of silicon sheet steel was developed in the early 1930's [Franklin, 1983], and the first commercial quantities introduced in 1939 [Heathcote, 1998].

During the 1970's Hi-B steel was introduced [Allan, 1991], and by 1995, this steel type was the norm in the industry [Heathcote, 1998].

Laser scribed core material was introduced from the 1980's (Figure 13) as a special material to be used only where the cost of core losses was very high [Heathcote, 1998].

Although the lowest predicted thickness of steel was 0.18 millimetres from approximately the 1990's (Figure 13), the lowest available thickness in the early 2000's was 0.23 millimetres [Kulkarni, 2004].

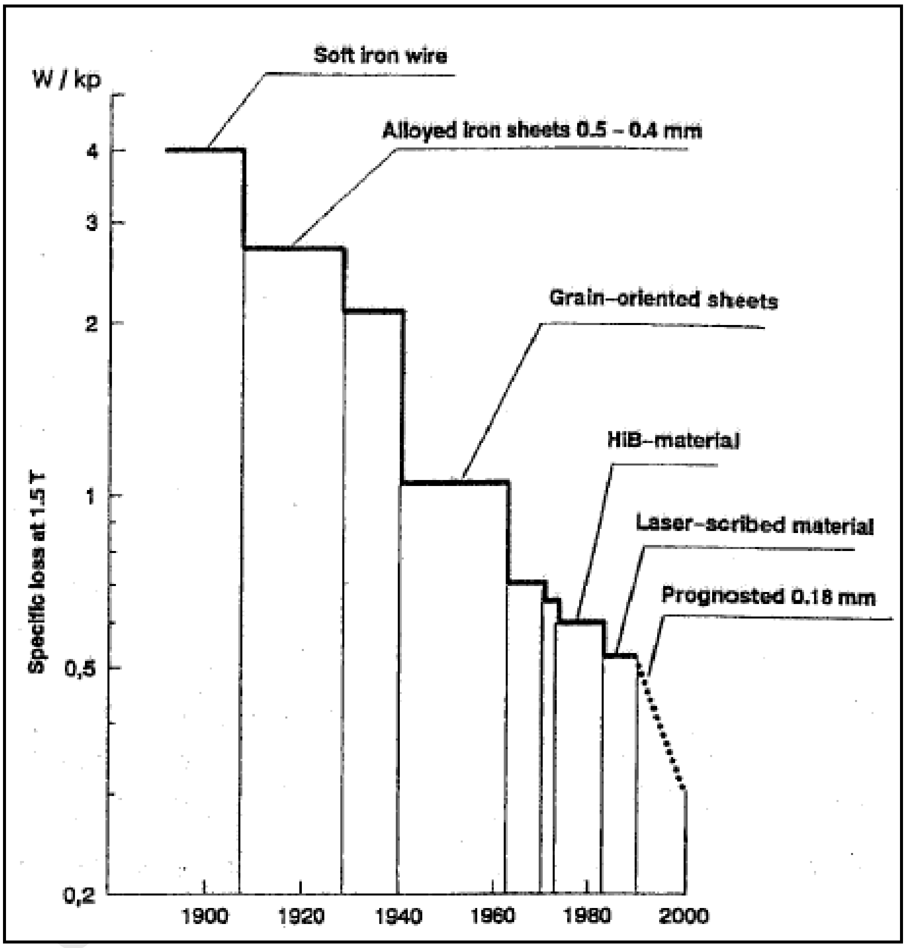


Figure 13: Overview of core steel development [Baehr, 2001]

3.2.2. Conductor Material

Improvements in conductor material were driven by the increase in power rating and voltage requirements due to increased electricity demands (Figure 14) and the reduction of eddy current losses and circulating currents [Allan, 1991, Baehr, 2001]. The increase in rated power and voltage was much steeper after the 1960's (Figure 14).

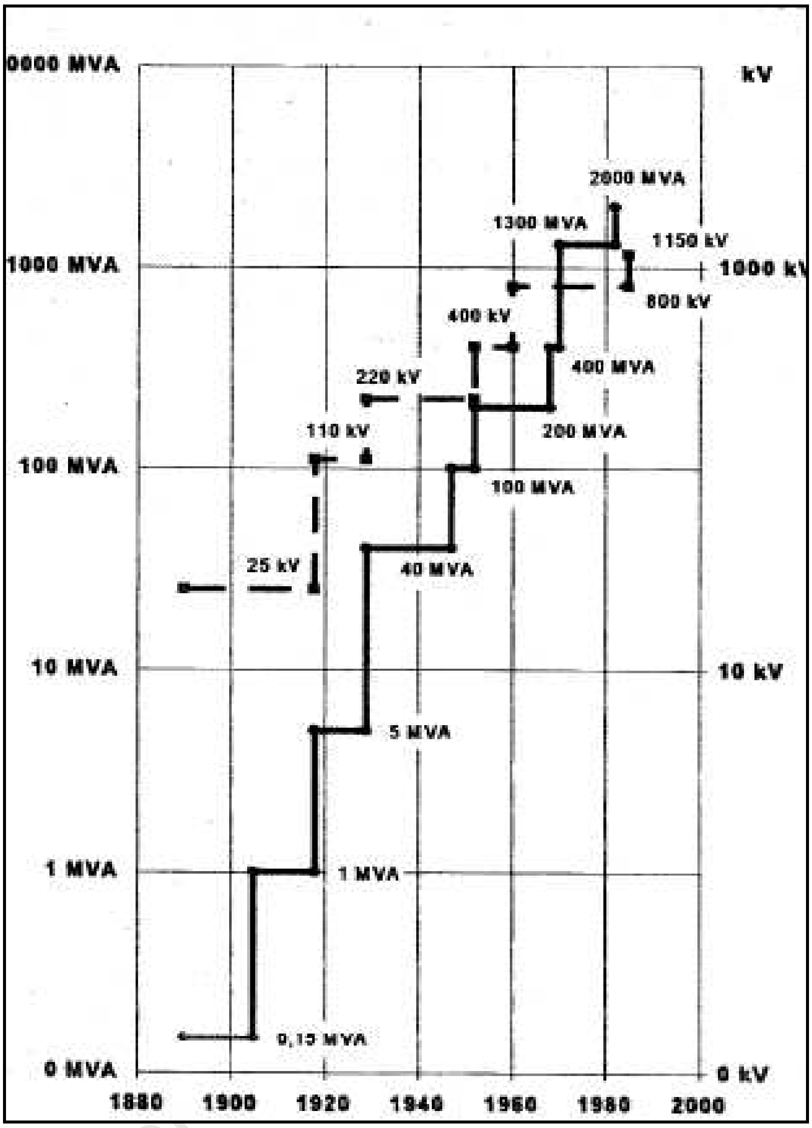


Figure 14: Overview of increase in transformer rated voltage and power [Baehr, 2001

As power ratings increased, low voltage windings using conductors connected in parallel were used to reduce eddy current losses [Allan, 1991]. At higher current values, conductors were transposed (continuously transposed conductor) during the 1960's, to avoid circulating currents caused by leakage flux linking with parallel connected conductors [Allan, 1991]. The transposition ensures that each strand experiences the same overall leakage flux, as nearly as possible [Heathcote, 1998]. Continuously transposed conductor is preferably of the epoxy bonded type for greater short circuit strength [Kulkarni, 2004].

According to Seay [2006], the IEEE C57 standards of 1975 resulted in new winding materials and mechanical designs.

3.2.3. Insulation Material

Paper-mineral oil based insulation systems have remained the most widely used, and according to Baehr [2001] and Metha [2006] this is mainly because of their high reliability and comparatively low prices. The available paper insulation technologies (in 1998, based on publication date of reference) include Kraft paper, creped paper, highly extensible paper, thermally upgraded paper and diamond dotted paper [Heatcote, 1998].

The development of high density pre-compressed boards (major insulation) has improved short circuit withstand [Metha, 2006].

No time periods were provided for these developments.

3.2.4. Tap Changers

Tap changers have traditionally been of the oil type. Development of the vacuum tap changer technology began in the 1980's, and was launched into the market in the mid 2000's [MR, URL1].

The vacuum tap changer technology offers a maintenance and operational advantage. The vacuum tap changer technology can offer up to 300,000 maintenance free tap operations and is significantly higher than for oil tap changers [MR, URL1].

The vacuum tap changer technology offers a big maintenance advantage since it eliminates arc quenching in oil associated with traditional oil tap changers. With the vacuum tap changer technology, the arc quenching takes place in the vacuum interrupters, resulting in cleaner diverter oil and reduced maintenance activities on the tap changer [ABB AB Components, 2008].

Because maintenance requires intrusive work to be done on the tap changer, outages are required to perform the work; the vacuum technology extends the maintenance intervals resulting in a reduction in outages.

Variations of the vacuum tap changer technology include retrofitting of the diverter switch (vacuum technology) into an existing oil type selector [ABB AB Components, 2008].

3.2.5. Bushings

The changes in bushing technology were driven from a maintenance and operational improvement perspective.

Early bushings were dry insulated, and produced from a resin coated paper, referred to as resin bonded paper bushings [Jonsson, 2006]. These bushings were wound in an uncontrolled workshop environment and as a result had a high partial discharge and dissipation factor [Jonsson, 2006].

From the 1940's, oil impregnated paper bushings with porcelain as the external insulator were introduced [Jonsson, 2006].

During the 1990's, resin impregnated paper bushings with a silicone rubber insulator were introduced to eliminate the problems experienced with oil impregnated paper types with porcelain insulators [Jonsson, 2006]. The advantages of silicone rubber over porcelain include the following: maintenance free since cleaning of the insulator in polluted areas is not required, self extinguishing properties, and hydrophobicity [ABB Components, 2005].

3.2.6. Condition Monitoring

Approximately since the 1980's (based on the publication date of the paper), transformer technology development has focussed on the necessary tools and equipment for condition monitoring and diagnosis of transformers [Baehr, 2001]. Condition monitoring techniques have developed to such an extent that the condition of all major parts of the transformer can be assessed. These techniques cannot prevent failure of transformers, but they can prevent the costly repercussions associated with transformer failures by allowing the user to take corrective action during the operating life.

3.3. DEVELOPMENTS IN DESIGN

Since the 1960's, numerical methods (finite difference) or analogue methods (resistance networks or electrolytical tank) were used to solve complex three dimensional partial differential equations governing the electric, magnetic, thermal and hydraulic fields [Allan, 1987].

Computer aided design, employing techniques such as finite element analysis and draughting techniques, was introduced in the late 1980's to speed up design work, and to achieve more compact designs with the improvement of space factor through the effective use of active materials (copper, iron and insulation) [Allan, 1987, 1991].

These techniques allowed the design engineer to simulate the transformer operation under abnormal conditions, and to determine how materials and constructional features would react to abnormal service conditions [Allan, 1987].

3.4. DEVELOPMENTS IN MANUFACTURING

The developments in manufacturing were aimed at reducing manufacturing times [Allan, 1991].

3.4.1. Core Cutting and Annealing

Up to the 1970's, the annealing process was used whereby the cut core steel laminations were passed through an annealing furnace to reduce the additional loss due to mechanical stress introduced during the cutting process [Allan, 1991]. Burrs introduced during the cutting and slitting process were also ground away, and the sheets reinsulated to replace insulating coating removed during the burr grinding operation [Allan, 1991].

The annealing process has since been eliminated with the use of modern cutting and slitting machines, and the introduction of Hi-B steel, because the steel was easier to handle [Allan, 1991]. The additional insulating coating on the core steel sheets was also no longer needed because of the high surface resistance of the Hi-B steel [Allan, 1991].

From the late 1980's to the early 1990's (based on the publication date of the reference), cutting and slitting machines employed high quality silicone carbide, that was aimed at improving the quality of the core edge and reducing operating costs [Allan, 1991].

3.4.2. Drying

Vapour phase drying was introduced in the 1940's. It has the advantage that it reduces the drying time by a factor of 3 to 6, depending on the size of the transformer, and it provides a more uniform dryness though all parts of the insulation [Allan, 1991] .

Since the 1950's, major improvements have been made in oil drying plants, and it became possible (from the late 1980's to early 1990's, based on the publication date of the reference) to impregnate a transformer in the factory in a vacuum below 0.03 millibar, using hot transformer oil with a water content below 2 parts per million in an air content below 2%, and with no fibrous particles in suspension [Allan, 1991].

3.4.3. Winding Construction and Conductor Material

Most manufacturers adopted disc type windings to reduce costs; they also require less labour to complete, but require additional techniques (application of electrical interleaving or inter-shielding) to provide adequate lightning impulse strength at the higher voltages [Allan, 1991].

The introduction of vertical winding machines allowed windings to be manufactured with less handling by the operator [Allan, 1987].

Measures implemented to achieve greater mechanical strength were hardening procedures during the manufacturing process of the copper conductor strands, which resulted in controlled increase of the yield point of copper conductor [Baehr, 2001].

No time periods were provided for these developments.

3.4.4. Clamping Structure

To account for the loss in clamping during the drying process, manufacturers applied an external clamping force [Allan, 1991]. This was originally done by hand by clamping down the winding by a force applied through tie rods between clamping rings. Techniques now being used by manufacturers include the use of large hydraulic presses to clamp down the winding, and the development of isostatic clamping techniques where the winding is subjected to a constant clamping force throughout the drying cycle [Allan, 1991]. No time periods were provided for these developments.

Cores were originally constructed using bolted frames to clamp the laminations together. Bolts have since been eliminated, first on core limbs, and then the yokes, from the 1950's to the 1970's. The laminations are (since the late 1980's or early 1990's based on the publication date of the reference) held together by the hoop stress of the windings, by fibre glass or metal banding (with an insulated insert), or by pinching the yoke laminations between external clamps [Allan, 1991].

3.5. RELATIONSHIPS BETWEEN RELIABILITY AND MANUFACTURING PERIODS

The surveyed failure statistics in chapter 2 indicated no change in terms of the major contributors of failure with manufacturing period. Due to the constraints also discussed in chapter 2, in particular the definition of the manufacturing period of the failed transformers in the surveyed literature, it was difficult to draw any meaningful inference on the relationship between reliability (failure patterns) and manufacturing periods. However, Bossi [1983] provided the most complete account of pre 1978 manufactured transformer failures. In order to relate the developments to transformer reliability, the pre and post 1980 periods will be compared.

3.5.1. Pre 1980

3.5.1.1. Power System Expansion

The exponential increase in rated power and voltage of transformers is directly related to power system expansion. According to Seay [2006], pre 1970 manufactured transformers did not perform well under increasing short circuit stresses resulting from power system expansion. The impact of short circuit forces on a transformer can usually be seen in the windings.

Failure statistics and developments supporting the impact of power system expansion on windings in this period include:

1. An increasing failure rate by year from the late 1960's up to the 1970's [Bossi, 1983]
2. Failures classification indicated that winding related failures were among the major contributor of failure location, and mechanical and dielectric type failures as failure modes; these are characteristic of the impact of short circuit forces on the windings and their insulation (winding movement or deformation, and premature aging of the winding insulation under repetitive short circuit forces).
3. The need for increased short circuit strength was acknowledged with the introduction of continuously transposed conductors during the 1960's.

Sufficient clamping of the transformer allows it to withstand the impact of short circuit forces. The developments in drying of the winding paper insulation since the 1940's (although reducing the impact of moisture on the winding insulation) could have resulted in a loss of clamping and short circuit withstand.

3.5.1.2. Magnetic Circuit/ Core Reliability

The constant development in core technology (material) had a positive impact on reliability and this is evident in the results in from the surveyed failure statistics, where core related problems featured as a minor contributor of failure, irrespective of manufacturing period.

Pre 1970 core problems related to design and manufacturing of the core, in particular to the understanding of leakage flux, also affected other parts of the transformer such as the windings. Significant developments in core design and manufacturing were only implemented after the 1980's, when problems related to leakage flux were understood

[Allan, 1987]. Larger transformers (GSU and transmission transformers) designed and built in the 1960's were failing from the 1980's, due to circulating currents in the unforeseen parallel circuits formed in the continuously transposed conductor [Allan, 1987]. This suggests that contributions of winding and core related failures of earlier transformers could have been differently classified if failure had initially been identified as being related to the core.

3.5.1.3. Impact of Design Techniques

Design related problems were a major contributor of failure in pre 1978 manufactured transformers irrespective of application [Bossi, 1983]. Analysis of the failure rate with age over the period 1955 to 1977 indicated a high early life failure rate, indicative of design or manufacturing related problems [Sokolov, 2005-2]. Allan [1987] attributed the failures of large transformers from the 1960's, to the inability to investigate the effects of abnormal service conditions during the design phase. This suggests that numerical design techniques used at the time were not effective.

However, Kogan [1988] demonstrated a contradicting opinion regarding the effectiveness of pre 1980 design techniques. Lower early life failure rates were observed in higher voltage units manufactured prior to 1977, which have been attributed to the fact that manufacturers built more margins into the designs, by testing units at higher lightning and induced test levels than required by the specification.

3.5.1.4. Tap Changer Reliability

Tap changer related failures featured among the major contributors in pre 1978 manufactured substation transformers [Bossi, 1983], and the surveyed literature also indicated that these were observed irrespective of manufacturing period. Failure statistics and developments in this period that could have contributed to poor tap changer reliability are:

1. Maintenance related problems were identified as a failure cause in pre 1978 manufactured substation and autotransformers; although they were not related to any specific location in the transformer.
2. The tap changer technology used during this period was the oil type tap changer. With switching of the diverter contacts in oil type tap changers, carbon particles are produced as by products in the diverter oil. Tap changer diverters are usually designed to operate under these conditions, but in extreme cases the carbon particles may reach levels that are

detrimental to the tap changer diverter, causing flashovers. As a result of the contamination and consequences, oil tap changers have to be maintained regularly. According to manufacturer specifications, tap changers can either be maintained based on a certain number of tap operations reached or a certain number of years from commissioning or last maintenance, whichever of the two comes first.

3. Tap changer maintenance involves intrusive work with human intervention, typically involving removal of the diverter switches, cleaning of the diverter contacts and replacement of the diverter oil. With human intervention and the nature of the tap changer maintenance, it is possible that foreign particles or items may find their way into the diverter tank. Switching operations take place in the diverter tank, and should there be foreign items, these could result in flashovers, compromising the tap changer operation.

3.5.1.5. Bushing Reliability

Bushing reliability in the pre 1980 period could be attributed to the technology being used, which was the oil impregnated paper type with porcelain insulator. The porcelain insulator in particular has the following weaknesses:

- Pollutants and moisture deposits can contaminate the surface of the porcelain bushing insulators, causing flashovers along the insulator, or between phases.
- According to Horning [2001], flashovers of an insulator occur when most of the surface is covered with a wet contaminant layer of resistivity. As the flashover process develops, tracking may occur which can cause cracks or punctures to develop on the insulator surface. This allows moisture ingress into the condenser body which causes it to deteriorate. Saline pollution can cause abnormal corrosion of bushing flanges and fittings, leading to hermetic seal deterioration that also causes atmospheric moisture ingress, allowing the bushing condition to degrade with time. Industrial pollution produces irregular surface voltage grading, which stresses the high voltage insulation, promoting flashovers along the bushing or between phases, and insulation damage.
- Due to this problem, the surface of porcelain bushing insulators has to be maintained regularly in areas where bushings are exposed to these

conditions. The maintenance activities on bushings involve external cleaning (hand wiping, washing with specialised equipment), or treating of the porcelain insulator with dielectric compounds.

- Although no intrusive work is done on the bushing, handling of the bushing can incur damage to the porcelain, or the condition of existing cracks and punctures may be worsened. This allows moisture ingress into the condenser body which causes it to deteriorate.

According to Sokolov [1997] approximately 80% of bushing failures in the period 1986 to 1996 (the pre 1986 build) occurred after 10 to 12 years in service, where design deficiencies and aging were typically involved. The contribution of pre 1980 manufactured bushings is not known, so it is not known whether the problems described are representative of the pre or post 1980 build. If the pre 1980 build was the major contributor, this could suggest that the design techniques used at the time were not sufficient.

3.5.1.6. Cooling System

According to Doble Engineering [2006], known weaknesses less likely to cause failure in pre 1970 transformers included corrosion in radiators and piping, and wear and failure of pumps and fans.

3.5.2. Post 1980

3.5.2.1. Winding Failures

As discussed in the previous sections, developments related to the windings included improved clamping techniques, drying of winding insulation, winding construction, manufacturing of the conductor and standardisation of winding material and mechanical designs. Despite these developments, winding related failures were still a major contributor, irrespective of manufacturing period which suggests that they had no impact on improving the reliability. Possible factors which could have caused the contribution of winding related failures to remain unchanged are discussed below.

1. Power system expansion was much steeper in the post 1980 era, as seen in Figure 14 which shows the increase in the rated power and voltage of transformers. With this steeper increase, the short circuit stresses that transformers experienced also increased significantly.

2. Modelling of abnormal service conditions with computer aided techniques was not a true reflection of what transformers were experiencing.

3. With the increase in rated power and voltage, larger sized transformers were also required, and design engineers had to take the transportation limits (rail, shipping and road transportation) into consideration in the complete design of the transformer [Bruce, 1968]. With optimisation of the transformer design using computer aided design techniques, internal clearances could be reduced, resulting in lower oil volumes and a reduction in insulation material; this has since led to dielectric and thermal mode failures becoming more prevalent [Seay, 2006]. This observation is evident in the surveyed studies in chapter 2, where dielectric mode failures featured as a major contributor of failure modes, irrespective of manufacturing period.

3.5.2.2. Tap Changer and Bushing Reliability

The surveyed literature indicated that substation transformers were prone to tap changer and bushing related failures, irrespective of manufacturing period.

Power system expansion is the result of increased demand for electricity, for households and industries. Since the porcelain insulator bushing technology was used in both manufacturing periods, the bushing related failures in the post 1980 period could be attributed to increased industrial pollution due increasing industries (mining, fossil fuelled power generation, industrial factories etc.). More pollution and the associated impact on bushing insulators could have made the bushings more susceptible to failure.

With reference to the discussion in section 3.5.1.5 on bushing design related deficiencies in the pre 1980 period , if the contribution of post 1980 bushings dominated, this could suggest that optimised bushing design using computer aided techniques introduced unforeseen weaknesses.

Significant developments in bushing and tap changer technologies were implemented from the 1990’s and 2000’s respectively. The impact of the new technologies on reliability could not be assessed for the following reasons: the surveyed studies in chapter 2 span up to 2005, suggesting that there has been 5 to 15 years experience with the two new technologies. However, the studies did not indicate what technology was being used. It could be assumed that the poorer reliability indicated by the studies was predominantly due to older technologies.

3.6. DEVELOPMENTS IN THE SPECIFICATION OF TRANSFORMERS

Eskom Distribution has made a number of changes in their design specification since the 1990's [Eskom Distribution, 2007]. The specification covers the design and testing requirements for Distribution transformers from 1MVA up to 160MVA. According to Distribution, the first transformer design specification was compiled in 1972. Versions of the specification prior to 1997 followed very much the IEC and BSI standards for transformers. The 1997 version is the original document from which all the later revisions were created, including contemporary ones. Major changes have been made since 1999, with later revisions including unique requirements.

Since 1999, the specification requires that transformers have a nominal design life of 35 years. The components and design aspects addressed in the Distribution transformer specification in the period 1999 to 2006 are given in Table 6. In addition to these, Distribution also introduced detailed design reviews for the thermal, insulation and short circuit design aspects of all transformers from the mid 2000-2009 decade.

Significant changes related to tap changers and bushings include the specification of the vacuum tap changer technology and resin impregnated paper bushings with silicone rubber insulator from 2005.

The other significant change implemented in the mid decade 2000-2009, related to bushings was to the bushing creepage. Bushing creepage changes were aimed at reducing the occurrence of surface discharges. The bushing creepage distance was adjusted 31kV/mm to withstand the heavy pollution in some areas. According to IEC [1986], the electrical creepage distance increases with the level of pollution. The electrical creepage distance is the shortest path between two conductive parts measured along the surface of the insulation. A proper and adequate creepage distance protects against the development of flashovers.

A new bushing specification was released in 2009 that applies to all transformers within Eskom, requiring the technology and creepage changes described above for transformers from 33kV [Eskom, 2009].

The effects of changes in the specification are only evident in new transformers that are manufactured 2 years after a revision is published. Since the first major changes occurred from 1999, the effects of these changes will only be seen in transformers manufactured from 2001.

Table 6: Component and design aspects addressed in Eskom Distribution specification from 1999 to 2006

YEAR	COMPONENT ADDRESSED BY CHANGE	DESIGN ASPECT ADDRESSED
1999	Surge Arrestors, Tank	Structural
2000	Windings, Insulation	Dielectric, Thermal
2002	Insulation, Bushing, Tap Changer	Dielectric, Thermal
2003	Insulation, Tap Changer	Dielectric, Thermal
2004	Winding, Insulation, Tank	Dielectric, Thermal
2005	Winding, Tap Changer, Bushings	Dielectric, Thermal
2006	Winding, Insulation, Core, Tap Changer, Bushings	Dielectric, Thermal, Mechanical

3.7. SUMMARY

Where possible, the known developments in transformer design, manufacturing and technology as presented in the literature were identified and their relationship to periods of reliability (failure) discussed. In summary, the following research questions/ aspects were addressed:

- Identifying the changes in transformer design, manufacturing and technology, and determining to what extent periods can be defined that could have had an impact on transformer reliability.
- Identifying the changes in the specification of transformers in South Africa.

The extent to which these questions were addressed is discussed below.

3.7.1. Reliability Related to Manufacturing Periods

Constraints in relating manufacturing periods with developments in design, manufacture and technology included lack of more detailed literature sources covering, in particular, developments within manufacturing periods.

The fact that the major contributors of failure have remained unchanged from the surveyed literature in chapter 2 could suggest that developments in design, manufacture and technology had no impact on reliability.

Because Bossi [1983] provided the most reliable account of failure statistics of older designs, two manufacturing periods were used to assess the impact of developments in design, manufacture and technology on transformers: pre and post 1980. Significant factors impacting on reliability in the two periods are summarised below.

3.7.1.1. Reliability Pre 1980

The significant contribution of winding related failures could be attributed to short circuit withstand being compromised due to the impact of increased operational stresses resulting from power system expansion, and developments in drying of transformer windings, and core design problems impacting on the windings.

The constant development in core material technology (and material) improved reliability, and this was evident in the surveyed statistics.

The two schools of thought regarding the effectiveness of earlier design techniques were represented in Allan [1987] and Kogan [1988]. Allan [1987] claimed that earlier design techniques were insufficient to model transformer operation under different operating conditions which caused different failure scenarios. Kogan [1988], on the other hand, claimed that the inability to optimise a design allowed more insulation margin into the designs which made them more reliable.

Poor tap changer and bushing reliability was affected by weaknesses associated with the technologies used at the time.

Problems related to the cooling system were less likely to lead to failure in pre 1970 manufactured transformers.

3.7.1.2. Reliability Post 1980

The surveyed failure statistics indicated winding related problems as a major contributor, irrespective of manufacturing period and transformer application, despite developments in manufacturing and materials. Factors that could have contributed to this unchanged behaviour include power system expansion (much steeper in this period), improper/insufficient modelling of abnormal service conditions, and a reduction in insulation margin due to optimised designs using computer aided techniques.

Poor tap changer and bushing reliability could be attributed to the fact there was no significant change in the technologies used up to the 1990's. It was assumed that the surveyed failure studies were based on these technologies. Bushing reliability appeared also to be affected by the ability to optimise the bushing design with computer aided techniques, which could have introduced unforeseen weaknesses.

Tap changers and bushing technologies underwent the most significant developments in the post 1980 period, and were aimed at eliminating problems experienced with previous technology.

3.7.2. Impact of Design Specifications

Eskom Distribution has implemented changes in the transformer design specification since the late 1990's. The relatively recent implementation of the revised specifications means the impact of improvements will only be seen in the failures of transformers manufactured from the early 2000's. A bushing specification for all transformer bushings in Eskom was also implemented in the late part of the decade 2000-2009 , and the impact of reliability will only be seen in future studies.

3.7.3. Next Steps

The next chapter will review the theory behind the statistical analysis measures, and assess its applicability to transformer failure data.

CHAPTER 4: STATISTICAL ANALYSIS OF FAILURE DATA

In chapter 2, statistical analysis methods were identified as a means of measuring transformer reliability. This included two types of failure rate: a failure rate for a group of transformers over a time period, and a time (age) dependent failure rate given by the hazard function. Statistical analysis is also used to determine the failure probability with age from the probability density function and the cumulative distribution function. Lapworth [2006] questioned the relevance of statistical analysis methods applied to transformer failure data.

This chapter will therefore review the theory behind these measures, and also investigate non parametric analysis techniques for representing data.

4.1. POPULATION AND SAMPLE

A statistical model describes some population [Nelson, 1982]. To obtain information, a sample (a set of units) from the population is used. The sample is analysed to get information on the underlying population distribution or to predict future data from the population.

4.2. FAILURE AND EXPOSURE MEASUREMENT

Data can be analysed according to each of a number of definitions of failure [Nelson, 1982]. It must be decided whether the time is calendar time or operating hours or some other measure of exposure, for example the number of start-ups, miles travelled, energy output, cycles of operation etc. Further, it must also be decided whether to measure time of exposure starting at the time of manufacture, or time of installation etc. [Nelson, 1982].

4.3. DATA TYPES

Proper data analysis depends on the type of data. Nelson [1982] described two main data types: complete data and censored data.

Complete data arise where the value of each sample unit is observed. Incomplete data or censored data arise where not all of the units in a sample have failed or the exact failure times of some units are unknown.

Nelson [1982] classified censored data into 9 data types as right censored, left censored, singly censored, multiply censored, time censored, failure censored, inspection data, and quantal response data.

The most relevant censored data types as described in Nelson [1982] are discussed below:

- *Right Censored Data:* Some units are un-failed and their failure times are known to only to be beyond their present running times. Un-failed units are called suspended unit, run-outs or removals.

- *Left Censored Data:* Units known to have failed before a certain time/date, whose failure time is not known.

- *Multiply Censored Data:* Data show differing running times intermixed with failure times, where units go into service at different times and have different running times when the data is recorded.

4.4. DESCRIPTIVE STATISTICS

Descriptive statistics is a branch of statistics that deals with data reduction techniques and provides insight into probability theory [Williams, 1991]. There are several topics within descriptive statistics which include the average (sample mean), the variability (sample variance), the correlation between two sets of sample data, and graphical techniques such as frequency and cumulative frequency plots. Frequency plots, also known as histograms, and cumulative frequency plots have traditionally been used to display data distributions, and illustrate the variable nature of data.

These two concepts are discussed and extended to that of relative frequency and cumulative relative frequency, as presented in Williams [1991].

4.4.1. Relative Frequency

Frequency refers to the number of occurrences in an interval [Williams, 1991]. The relative frequency of a distribution is determined by normalising the frequency in all intervals. The normalisation is achieved by dividing the frequency by the sum of the number of occurrences across all intervals.

Williams [1991] defined relative frequency as:

$$f_k = \frac{n_k}{n} \qquad 4.1$$

Where:

$k =$ Interval index

$n_k =$ Frequency of an interval

$n =$ Total number of occurrences across all the intervals

$f_k =$ Relative frequency of an interval

4.4.2. Cumulative Relative Frequency

Williams [1991] determined the cumulative frequency from frequency as follows:

$$N_k = \sum_{i=1}^{k} n_i \qquad 4.2$$

Where:

$k =$ Interval index

$n_i =$ Frequency of an interval

$N_k =$ Cumulative frequency of an interval

Williams [1991] determined the cumulative relative frequency from the cumulative frequency as follows:

$$F_k = \frac{N_k}{n} \qquad 4.3$$

$$F_k = \sum_{i=1}^{k} f_i \qquad 4.4$$

Where:

$k =$ Interval index

$n =$ Total number of occurrences across all the intervals

$f_i =$ Relative frequency

$F_k =$ Cumulative relative frequency

4.5. CONTINUOUS AND DISCRETE DISTRIBUTIONS

In statistical theory, there can be distinguished two types of distributions: discrete and continuous. Discrete data consists of distinct observations or measurement, whereas continuous data is a continuous set of numbers.

4.5.1. According to Nelson [1982]

A discrete distribution is a probability model Y, that consists of a list of distinct possible outcomes $y_1, y_2, y_3, ...$ etc., each with a corresponding probability $f(y_1)$, $f(y_2)$, $f(y_2)$, etc., and $f(y)$ is called the probability function.

The probabilities $f(y_i)$ have the following properties:

1) must be greater than or equal to zero
2) their sum must equal 1

A continuous distribution is a probability model Y, that consists of the possible numerical outcomes y that are a subset $\wp$ of the line $(-\infty, \infty)$, etc., and a probability density $f(y)$, function with the following properties:

1) $f(y) \geq 0$ for all y in $\wp$
2) $\int_{\wp} f(y)dy = 1$, where the integral runs over the range $\wp$

4.5.2. According to Williams [1991]

A continuous distribution comprises observations that are a continuous set of numbers obtained from a random experiment. For a continuous random variable, the probability of observing any specific number is vanishingly small.

Discrete distributions comprised of discrete observations:

$$S_X = \{x_1, x_2, x_3, ...\} \qquad 4.5$$

Where values of x_i are in a countable set (either finite or infinite) of numbers, and the random experiment is such that the probability of observing a specific $x_i \in S_X$ does not vanish:

$$P(X = x_i) = P(x_i) > 0\,, \qquad i = 1, 2, 3... \qquad 4.6$$

The probability associated with a discrete random variable is called a probability mass function. When all elementary discrete observations in a sample space are considered, their probabilities sum up to one:

$$\sum_i P(x_i) = 1 \qquad 4.7$$

4.6. CONCEPTS IN STATISTICAL LIFE DISTRIBUTIONS

Four of the primary concepts in statistical life distributions are the probability density function (PDF), cumulative distribution function (CDF), survival function (or reliability function) and the hazard function. These concepts will be discussed in this section as applied to continuous distributions.

4.6.1. Probability Density and Cumulative Distribution Functions

4.6.1.1. According to Nelson [1982]

The probability density function $f(y)$ is the mathematical model for the population histogram containing relative frequencies which must be greater than or equal to zero, and must sum up to unity.

A probability density $f(y)$ is a function of y with the properties

a. $f(y) \geq 0$ for all y in $\wp$ and;

b. $\int_{\wp} f(y)dy = 1$, where the integral runs over the range $\wp$

If y represents age at failure of a device, then a point on the probability density function may be interpreted as:

- percentage that failed at a certain age,
- probability of failure at a certain age,
- the mode of the distribution, i.e. the age at which failure is most likely to occur, is given by the maximum point on the probability density function.

The cumulative distribution function $F(y)$ for a continuous distribution with a probability density $f(y)$ is:

$$F(y) = P\{Y \le y\} = \int_{-\infty}^{y} f(u)du \qquad 4.8$$

where the integral runs over all outcomes less than or equal to y. The cumulative distribution function and probability density function are related by:

$$f(y) = \frac{dF(y)}{dy} \qquad 4.9$$

Any such cumulative distribution function has the following properties:

1) it is a continuous function for all y
2) $\lim_{y\to-\infty} F(y) = 0$ and $\lim_{y\to\infty} F(y) = 1$, and
3) $F(y) \le F'(y)$ for all $y < y'$

Relationships of probabilities of events expressed in terms of $F(y)$ are given below:

$$P\{Y \le y\} = \int_{-\infty}^{y} f(y)dy = F(y) \qquad 4.10$$

$$P\{Y > y\} = \int_{y}^{\infty} f(y)dy = 1 \qquad 4.11$$

$$P\{y < Y \le y'\} = \int_{y}^{y'} f(y)dy = F'(y) - F(y) \qquad 4.12$$

A point on the cumulative distribution function may be interpreted as:

- the probability of failure by a certain age,
- the age at which a proportion of the population has failed given by the 100th P^{th} percentile where $P = F(t_p)$.

4.6.1.2. According to Williams [1991]

From section 4.4.1, when we let the number of occurrences $n \to \infty$ and the intervals become arbitrarily small, then the relative frequency plot becomes a density function $f_x(x)$, given by the relation in 4.13 below:

$$f_k \rightarrow f_x(x)dx \quad 4.13$$

Similarly, the cumulative relative frequency in equation 4.4 becomes a cumulative distribution function $F_x(x)$:

$$F_k \rightarrow F_x(x) \quad 4.14$$

and is guided by:

$$F_x(x) = \int_{-\infty}^{x} f_x(\tau)d\tau \quad 4.15$$

The cumulative distribution function is a probability:

$$F_x(x) = P[a : X(a) \leq x] \quad 4.16$$

and read as the probability of outcome a such that observations obtained using random variable X are less than or equal to the independent random variable x. Using shorter notation, equation 4.16 may be rewritten as:

$$F_x(x) = P(X \leq x) \quad 4.17$$

and may be read as the probability that the random variable X is less than or equal to x.

Using equation 4.17, the properties of a cumulative distribution function include:

$$F_x(\infty) = P(X \leq \infty) = 1 \quad 4.18$$

$$F_x(-\infty) = P(X \leq -\infty) = 0 \quad 4.19$$

When we assume that a and b are two values on the real line, and that $a < b$, then the two events $X \geq a$ and $a < X \leq b$ are disjoint. Using the probability axioms:

$$P(a < X \leq b) = P(X \leq b) - P(X \leq a) \quad 4.20$$

$$P(a < X \leq b) = F_x(b) - F_x(a) \quad 4.21$$

The density function in the integrand of equation 4.15 is called the probability density function, and, using the fundamental theorem of calculus, it is expressed as:

$$f_x(x) = \frac{d}{dx}\int_{-\infty}^{x} f_x(\tau)d\tau \qquad 4.22$$

Using equation 4.15 to express equation 4.21 in terms of a PDF yields:

$$P(a < X \le b) = \int_{-\infty}^{b} f_x(x)dx - \int_{-\infty}^{a} f_x(x)dx \qquad 4.23$$

Combining the two integrals in equation 4.23 gives:

$$P(a < X \le b) = \int_{a}^{b} f_x(x)dx \qquad 4.24$$

It therefore follows if $b \to \infty$ and $a \to -\infty$, and equations 4.24, 4.18, 4.19 and 4.21apply, that the area under a PDF is always unity:

$$P(a < X \le b) = \int_{-\infty}^{\infty} f_x(x)dx = 1 \qquad 4.25$$

It also follows from equation 4.24 that if $a = x$ and $b = x + dx$, then $P(x < X \le x + dx)$ is a differential of probability dP:

$$dP = f_x(x)dx \qquad 4.26$$

4.6.2. Survival/Reliability Function

4.6.2.1. According to Nelson [1982]

The survival/reliability function of a continuous life distribution is:

$$R(y) = P\{Y > y\} = \int_{Y}^{\infty} f(y)dy = 1 - F(y) \qquad 4.27$$

If y represents age at failure of a device, then a point on the survival/reliability function may be interpreted as:

- The probability of surviving beyond a certain age y is $R(y)$,
- Percentage of that survived at least until age y,
- The survivorship at age y is $R(y)$.

4.6.2.2 According to Williams [1991]

The reliability is defined as the probability of a device failing after time t, and is given by:

$$R(t) = P(T > t) \quad 4.28$$

The probability of a device failing between time zero and some non negative time t is given by the cumulative distribution function as:

$$F(t) = P(T \leq t) = P(0 \leq T \leq t) = \int_0^t f(\tau)d\tau \quad 4.29$$

Using equation 4.29, $R(t)$ can be rewritten in terms of the CDF as:

$$R(t) = 1 - F(t) \quad 4.30$$

And as:

$$R(t) = 1 - \int_0^t f(\tau)d\tau \quad 4.31$$

$R(t)$ is defined such that $0 \leq t < \infty$ and $y = R(t)$ defined such that $0 \leq R \leq 1$. The reliability function may be interpreted in two ways:

1) When one device is put in service at time zero, the probability the device will last more than t units of time is $R(t)$. Or the probability that the device will fail before t is $1 - R(t)$.
2) When many of the same devices are all put in service at time zero, the fraction $R(t)$ of them will continue to function after t units of time. Or that a fraction $1 - R(t)$ will fail before time t.

4.6.3. Hazard Function

4.6.3.1. According to Nelson [1982]

The hazard function $h(y)$ of a continuous distribution of life Y with a probability density is defined for all possible outcomes y as:

$$h(y) \equiv \frac{f(y)}{1-F(y)} = \frac{f(y)}{R(y)} \qquad 4.32$$

It is the instantaneous failure rate at age y, that is, in the short time Δ from y to $y+\Delta$, a proportion $\Delta \cdot h(y)$ of the population that reached age y fails. The hazard function is a therefore a measure of the proneness to failure as a function of age, and is also called the hazard rate, mortality rate and the force of mortality.

Any function satisfying the following properties is a hazard function of a distribution:

- $h(y) \geq 0$ for $-\infty < y < \infty$
- $\lim_{y \to -\infty} \int_{-\infty}^{y} h(y)dy = 0$ and $\lim_{y \to \infty} \int_{-\infty}^{y} h(y)dy = \infty$

A decreasing hazard function during the early life of a product corresponds to infant mortality. This often indicates that the product is poorly designed or suffers from manufacturing defects.

An increasing hazard function during later life of a product is said to correspond to wear-out failure. Such failure rate behaviour often indicates that failures are due to the product wearing out.

A hazard function showing a decreasing failure rate in the early life and an increasing failure rate in later life is referred to as a bathtub curve by reliability engineers, as shown in Figure 15.

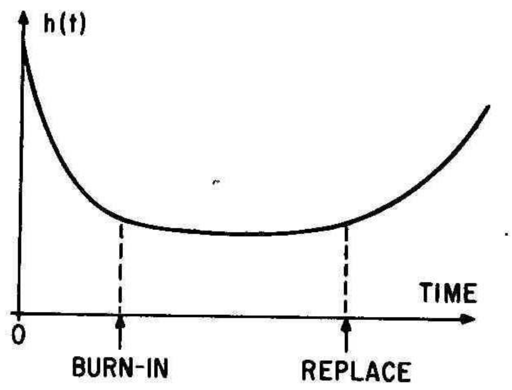


Figure 15: Bathtub curve [Nelson, 1982]

4.6.3.2. According to Williams [1991]

The hazard function is related to the probability of a device failing within an interval $t < T \leq t + dt$ given that the device is operating properly at time t, t a non-negative integer.

This conditional probability may be expressed first using the concept of relative frequency and the definition of conditional probability. Using the concept of relative frequency:

$$P[(t < T \leq t + dt) \mid (T > t)] = \frac{dn}{n(t)} \qquad 4.33$$

Where:

$n(t) =$ number of devices that are operating properly at time t

$dn =$ number that fail in the interval between t and $t + dt$

The second description uses the definition of conditional probability:

$$P[(t < T \leq t + dt) \mid (T > t)] = \frac{P[(t < T \leq t + dt) \cap (T > t)]}{P(T > t)} \qquad 4.34$$

The joint probability $P[(t < T \leq t + dt) \cap (T > t)]$ in equation 4.34 is evaluated by noting that the event $(t < T \leq t + dt)$ is contained within $(T > t)$, so that the intersection of the two events is $(t < T \leq t + dt)$.

Since $P(t < T \leq t + dt)$ is a differential of probability $dP = f(t)dt$ (refer to the derivation of equation 4.26) and using equation 4.28, equation 4.34 becomes:

$$P[(t < T \leq t + dt) \mid (T > t)] = \frac{f(t)dt}{R(t)} \qquad 4.35$$

Combining equations 4.33 and 4.35 yields:

$$\frac{dn}{n(t)} = \frac{f(t)dt}{R(t)} \qquad 4.36$$

Rearranging this equation gives the definition of the hazard function in terms of the PDF and reliability function:

$$h(t) = \frac{1}{n(t)}\frac{dn}{dt} = \frac{f(t)}{R(t)} \qquad 4.37$$

Some general features of the hazard function are illustrated in Figure 16.

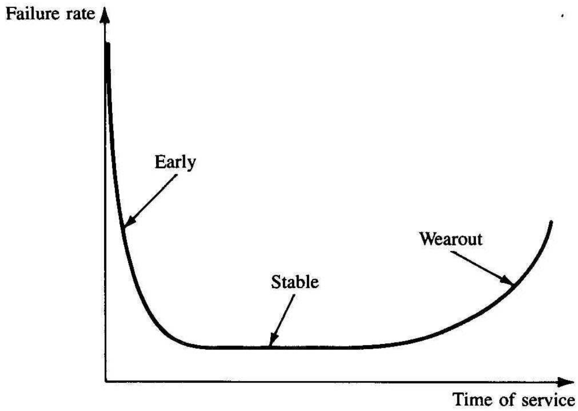


Figure 16: An idealized plot of the failure rates of a manufactured device [Williams, 1991]

The curve in Figure 16 is generally referred to as the bathtub curve where initially the failure rate tends to be high because of manufacturing flaws which often reveal themselves in early life of a device. The device goes into a stable or steady state period when the early life flaws no longer appear and failure rates become constant or nearly so. In the wear-out period, the cumulative effects of wear appear and the failure rate begins to increase.

4.7. FAILURE RATE AND INSTANTANEOUS FAILURE RATE

Two types of failure rate were identified in chapter 2: a failure rate for a group of transformers over a time period, and a time (age) dependent failure rate given by the hazard function.

4.7.1. According to Nelson [1982]:

The hazard function gives the instantaneous failure rate with age, as discussed in section 4.6.3.1.

4.7.2. According to Bossi [1983]:

Failure rate was expressed with the following formula:

$$\lambda = 100 \cdot \frac{\sum_i n_i}{\sum_i N_i} \% \qquad 4.38$$

Where:

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

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

4.7.3. According to Tobias [1986]:

Williams [1991] cites Tobias [1986] in the definition of average failure rate.

An average failure rate typifies failure rate behaviour over an interval. The average failure rate between time t_1 and t_2 is found by integrating the instantaneous failure rate obtained from the hazard function over the interval, and the dividing $t_2 - t_1$ as shown below:

$$AFR(t_1, t_2) = \frac{\int_{t_1}^{t_2} h(t)dt}{t_2 - t_1} = \frac{H(t_2) - H(t_1)}{t_2 - t_1} = \frac{\ln R(t_1) - \ln R(t_2)}{t_2 - t_1} \qquad 4.39$$

Where $H(t)$ is the cumulative hazard function obtained by integrating over the hazard function and $R(t)$ the reliability function.

4.7.4. According to IEEE [1986]:

Failure rate is defined as: The ratio of the number of failures with forced outages of a given population over a given period of time, to the number of accumulated service years for all transformers in that population over the same period of time.

The definition of failure rate is dedicated to transformers and shunt reactors, and defined for failures with forced outages.

IEEE [1986] defines failure with forced outages as: Failure of a transformer that requires its immediate removal from service, which is accomplished either automatically or as soon as switching operations can be performed.

As a note to this definition, IEEE [1986] states the following: The failure rate defined here is composed for ‘failures with forced outages’. This is used for statistical analysis in system mathematical studies. Other reports may be made using ‘failure with scheduled outages’ and ‘defects’. Tabulation of scheduled outages and defects needs to be aggressively pursued from the standpoint of reliability improvement. It should be recognized that reliability improvement is different from reliability measurement. Quantitative, mathematically correct, reliability measurement can only be accomplished by counting ‘failures with a forced outage’. Reliability improvement, on the other hand, can be accomplished through tabulating and reporting a wide variety of problems. Terms such as ‘failures with a scheduled outage’ and ‘defects’ fall into this area of quality reporting and should not be used to develop the statistic called ‘failure rate’. Defects and failures with a scheduled outage should be tabulated for purposes of immediate and ongoing feedback to manufacturers and operating groups for the improvement of reliability.

4.7.5. According to IEC [1990]:

Instantaneous failure rate is defined as: The limit, if it exists, of the quotient of the conditional probability that the instant of a failure of a non-repaired item falls within a given time interval $(t, t+\Delta t)$ and the duration of this time interval, Δt, when Δt tends to zero, given that the item has not failed up to the beginning of the time interval.

The instantaneous failure rate is expressed by the formula:

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} \frac{F(t+\Delta t) - F(t)}{R(t)} = \frac{f(t)}{R(t)} \qquad 4.40$$

where $F(t)$ and $f(t)$ are respectively the distribution function and the probability density of the failure instant, and where $R(t)$ is the reliability function, related to the reliability $R(t_1, t_2)$ by $R(t) = R(0,t)$.

An estimated value of the instantaneous failure rate can be obtained by dividing the ratio of the number of items which have failed during a given time interval to the number of non failed items at the beginning of the time interval, by the duration of the time interval.

The mean failure rate is the mean of the instantaneous failure over a given time interval (t_1, t_2) and is expressed by the formula:

$$\bar{\lambda}(t_1,t_2)=\frac{1}{t_2-t_1}\int_{t_1}^{t_2}\lambda(t)dt \qquad 4.41$$

4.7.6. According to Elerath [2000]:

Three failure rate terms were described:

- average failure rate,
- annual failure rate,
- annualised failure rate.

The problem with these three terms is that the concepts are not independent. In some circumstances, an average failure rate is equivalent to an annual failure rate, but using other assumptions it is not. Annual and annualised failure rates are equivalent if the time over which the average occurs is 1 year.

Where the instantaneous failure rate given by the hazard function is not constant in time, average, annual or annualised failure rates are highly dependent on the time period over which the data is collected.

The definitions are described in terms of a disk drive framework.

The average failure rate is the integral of the instantaneous failure rate given by the hazard function, divided by the width of the interval and calculated as:

$$\text{Average Failure Rate}=\frac{\text{Total number of failures in interval }(T_1,T_2)}{\text{Total cumulative drive calendar time in interval }(T_1,T_2)} \qquad 4.42$$

The annual failure rate is similar to the average failure but the interval is 1 year. The annual failure rate is determined as follows:

$$\text{Annual Failure Rate}=\frac{\text{Total number of failures in 1 year}}{\text{Total calendar drive hours accumulated in 1 year}} \qquad 4.43$$

The annualised failure rate is an estimate of the annual failure rate based on extrapolating beyond the period of time that data was collected, and normalising to 1 year.

The annualised failure rate is calculated as follows:

$$\text{Annual Failure Rate} = \frac{\text{Total number of failures in } m \text{ months}}{\text{Total calendar drive hours accumulated in } m \text{ months}} \cdot E_f \qquad 4.44$$

E_f is a factor or function that allows extrapolation beyond the interval over which data was collected to permit stating the annualised failure rate for an entire year. Extrapolations may try to account for failure rates that are constant, or linearly or non-decreasing in time.

4.8. NON PARAMETRIC DATA ANALYSIS METHODS

Parametric data analysis involves fitting a theoretical distribution to data. Some of these continuous theoretical distributions include the exponential, normal, lognormal, and Weibull distributions.

In contrast, non parametric data analysis results when no theoretical distribution is fitted to the data and no particular mathematical form of the distribution is assumed. Non parametric analysis helps spot unusual data; the peculiar appearance of a bad data plot or certain plotted points may reveal bad data or yield important insights when a cause is determined. It also aids in assessing the assumptions of analytical methods applied to data.

Some limitations of non parametric data analysis in comparison with parametric methods follow, from Nelson [1982]:

- It is not objective; two people using the same plot may obtain somewhat different estimates, but they usually come to the same conclusion.
- It does not provide confidence intervals or a statistical hypothesis test; however a plot is often conclusive and leaves little need for such analytical results.

Two non parametric data analysis methods will be discussed: probability plotting and hazard plotting.

4.8.1. Advantages of Probability and Hazard Plotting

Despite the limitations of non parametric methods, they have some advantages listed below from Nelson [1982]:

- Apply to both complete data and censored data
- Fast and simple to use, and present data in an easy to grasp form.

- Provide simple estimates for a distribution such as percentiles, parameters, nominal life, failure rate and my other quantities techniques apply to both complete data and censored data.
- Help spot unusual data; the peculiar appearance of a bad data plot or certain plotted points may reveal bad data or yield important insights when a cause is determined.
- Test the assumptions of analytical methods applied to data.

4.8.2. Probability Plotting

Probability plotting involves generating plotting points from running time and failure time data to produce a sample CDF for complete data, and a sample reliability function for censored data.

The data points are plotted on probability papers. On probability paper, the data and cumulative probability scales are constructed so that any such theoretical CDF draws a straight line through the data.

If a straight line does not fit the data well on any of the available probability papers (exponential, normal, lognormal, Weibull), then a smooth curve may be drawn through the data points. This is referred to as a non parametric fit because no particular mathematical form of the distribution is assumed.

4.8.2.1. Probability Plotting of Complete Data

Probability plotting yields a sample CDF for complete data which is used to estimate the population CDF. The value of the population CDF at a given time is the population fraction failing by that time. Similarly, the sample CDF at a time is the sample fraction failing by that time [Nelson, 1982].

From Nelson [1982], the sample CDF is constructed as follows:

1. Order the n failure times from smallest to largest.
2. Assign a rank to each failure. Give the earliest rank 1, the second failure rank 2 etc., and the last failure has rank n.
3. Calculate the probability plotting positions F_i. For the failure with rank n, the midpoint plotting position is:

$$F_i = 100 \cdot \left(\frac{i - 0.5}{n} \right) \% \quad , \; i = 1, \ldots, n \qquad 4.45$$

4. Probability plotting positions can also be calculated as:

$$F_i = 100 \cdot \left(\frac{i}{n} \right) \% \quad , \; i = 1, \ldots, n \qquad 4.46$$

5. Plot the data points on theoretical probability paper to obtain the parameters of a theoretical distribution.
6. If a straight line does not fit through the data points on any of the available probability papers, then draw a smooth curve to obtain a non parametric estimate.

4.8.2.2. Probability Plotting of Multiply Censored Data

Nelson [1982] described three methods of probability plotting for multiply censored data namely the Herd-Johnson, Kaplan-Meier and actuarial methods. Each method provides a non parametric estimate of the reliability function. The actuarial method is suited for larger samples where data is grouped into intervals, while the Herd-Johnson and Kaplan-Meier methods are suited for smaller samples since they plot the individual failure times.

The steps required to make an actuarial probability plot, from Nelson [1982], are given below:

1. Assign time intervals; intervals need not have the same length and intervals with no failures need not be tabulated.
2. For each interval determine the number of units that enter r_y, the number that fail f_y, and the number that are censored c_y. Determine r_{y+1} as $r_{y+1} = r_y - f_y - c_y$.
3. The sample reliability function estimate is calculated as:

$$R(y) = 1 - \left[\frac{f_y}{(r_y - 0.5c_y)} \right] \qquad 4.47$$

Where $R(0) = 1$.

4. The $-0.5c_y$ adjusts for the censored units, which run about half the interval.
5. The sample CDF can be derived from the reliability function using equations 4.27, as:

$$F(y) = 1 - R(y) \qquad 4.48$$

6. Plot the data points on theoretical probability paper to obtain the parameters of a theoretical distribution.
7. If a straight line does not fit through the data points on any of the available probability papers, then draw a smooth curve to obtain a non parametric estimate.

4.8.3. Hazard Plotting

Hazard plotting applies to both complete and censored data [Nelson, 1982]. They look like probability plots but their plotting positions are slightly different from probability plotting positions. Plotting points are generated from running time and failure times, depending on the type of data that is being dealt with, and the data points are plotted on hazard papers to produce a sample cumulative hazard function.

Similarly to probability papers, the data and cumulative probability scales of hazard papers are constructed so that any such theoretical cumulative hazard function draws a straight line through the data. If a straight line does not fit the data well on any of the available hazard papers (exponential, normal, lognormal, Weibull), then a smooth curve (non parametric fit) may be drawn through the data points.

Hazard plots provide information on the percentage failing by a given age, the percentiles of a distribution, as well as the nature of the failure rate as a function of age [Nelson, 1982], as shown in Figure 17.

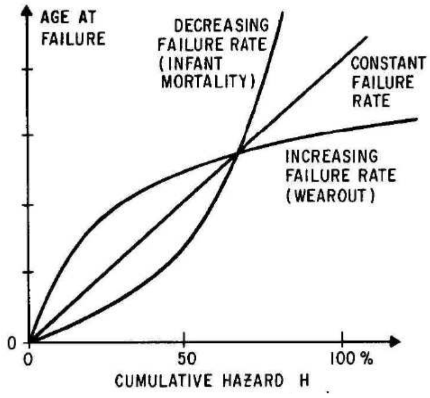


Figure 17: Nature of the failure rate obtained from the cumulative hazard function [Nelson, 1982]

The steps required to make a hazard plot from multiply censored data were described in Nelson [1982] as:

1. Order the running (censoring) times and failure times from smallest to largest, without regard to which is a censoring or failure time.
2. Label the times with reverse ranks; label the first time with n, the second $n-1$, etc. and the nth with 1.
3. Mark running times, for example with a '+'.
4. Calculate the hazard value for each failure time as $100/k$ where k is its reverse rank.
5. Calculate the cumulative hazard value as the sum of its hazard value, and the cumulative hazard value of the preceding failure.
6. Plot the data points on hazard paper to obtain the parameters of a theoretical distribution.
7. If a straight line does not fit through the data points on any of the available hazard papers, then draw a smooth curve to obtain a non parametric estimate.

4.9. SUMMARY

This chapter was aimed at reviewing the theory behind the statistical analysis measures identified in chapter 2. This was achieved by reviewing the following:

- Underlying assumptions of data analysis
- Derivation of the four primary concepts (probability density function, cumulative density function, survival function and hazard function) and information obtained from them

- Variations of the term failure rate
- Non parametric analysis techniques used to represent the primary concepts graphically

4.9.1. Data Types

The application of statistical analysis techniques is dependent on the data types. Two most relevant data types were identified: complete data and censored data (left censored, right censored and multiply censored).

4.9.2. Information Obtained from Primary Concepts

The following measures could be obtained from the four concepts:

- Probability of failure with age, obtained from the PDF and CDF.
- Probability of survivorship with age, obtained from the survival function.
- Instantaneous failure rate with age, obtained from the hazard function.

4.9.3. Variations of the Term 'Failure Rate'

Apart from the instantaneous failure rate obtained from the hazard function, there appeared to be a few variations of the term failure rate, which have been cited in various sources as:

- Average failure rate
- Annual failure rate
- Annualised failure rate
- Failure rate

4.9.4. Non Parametric Analysis Techniques

Probability and hazard plotting non parametric techniques can be used to represent the concepts graphically. These methods were applied to complete data and multiply censored data.

4.9.5. Next Steps

Based on the aforementioned, the following research questions / aspects will be addressed in the next chapters:

- Recommendations from international standards and guidelines on the treatment of failure data (definitions, data collection and classification) should be applied to transformer failures in South Africa.
- Assessing the applicability of the statistical analysis methods to the collected transformer data.

CHAPTER 5: DATA COLLECTION AND PREPARATION OF DATA FOR ANALYSIS

In this chapter, recommendations from international guidelines on the treatment of failure data (collection and classification) are applied to transformer failures in South Africa.

In chapter 5, recommendations from international standards and guidelines on the treatment of failure data (definitions, data collection and classification) are applied to transformer failures in South Africa, in preparation for the subsequent analysis. Based on the collected data, the impact of changes in the specification on reliability is also assessed.

5.1. DEFINITION OF FAILURE

Failure was defined as: The termination of the ability of an item to perform a required function such that it must be taken out of service.

Failure was also classified into outage types according to IEEE [1986] as:

- *Failures with forced outages:* Failure of a transformer that requires its immediate removal from service. This is accomplished either automatically or as soon as switching operations can be performed.
- *Failures with scheduled outages:* Failure for which a transformer must be deliberately taken out of service at a selected time.

In broader sense, the definition of failure and its classification in this study make provision for two types of failures:

- *Complete failures*: Complete failure of the transformer resulting in scrapping of the transformer (mostly severe type failures)
- *Failures with repair:* Failures that result in repair, upon which the transformer is replaced after repair (mostly intermediate and minor type failures). A single transformer may have multiple failures with repair.

5.2. FAILURES DATABASE

Before collecting the failures, as per the definition in section 5.1, it was necessary to decide on an appropriate format to capture the failure information. For this purpose, the format of the failure reporting form developed in Cigré WG A2.18 [2003], and referred to in chapter 2, was used.

The standard failure reporting form, developed by Cigré WG A2.18 [2003], grouped data into three categories as follows:

- *Equipment description:* serial number, substation/power station, unit number, rating, primary voltage, secondary voltage, tertiary voltage, year manufactured, manufacturer, model, number of phases, tap changer type, tap changer model, cooling system, oil conservation system, overvoltage protection, neutral earthing.
- *Operational history:* age, typical loading, loading immediately prior to failure, maintenance history, unusual events prior to failure, condition monitoring and assessment before/after failure.
- *Description of failure:* failure date, scheduled/forced outage, incident description, indication of failure, protection operated, failure location, investigation of failure, investigation findings, failure cause, nature of failure/failure mode, severity, repairs carried out, aging aspects, pre-existing faults, network conditions, weather conditions.

5.3. FAILURES CLASSIFICATION

The surveyed studies in chapter 2 classified failures into failure location, failure causes and failure modes. The classification format presented in Cigré WG A2.18, [2003] was used to classify the failures.

Failure location referred to the location in the transformer where the failure was initiated (Table 7).

Failure cause referred to cause of failure in the location where the failure was initiated (Table 8).

According to IEEE [1991], failure mode referred to the manner in which failure occurs, and was categorised as electrical, thermal, and mechanical and contamination. The description of the 'nature of failure' as used in Cigré WG A2.18 [2003] (Table 9) is similar to that of failure mode in IEEE [1991]. The nature of failure and failure mode will thus be considered as being equivalent, referring to the mode/nature of failure in the location where the failure was initiated.

Table 7: Failure locations classification [Cigré WG A2.18, 2003]

LOCATION	DESCRIPTION
Windings	
Winding Connections	Between windings Tap Leads To Bushings
Mechanical Structure	Clamping Coil Blocking Lead Support
Insulation	Major Minor Material - Liquid, Gas
Tank	
Tap Changer	Selector Diverter Drive Motor & Couplings Control System
Bushings	Porcelain Core Helmet Draw Lead
Magnetic Circuit	

Table 8: Failure cause classification [Cigré WG A2.18, 2003]

FAILURE CAUSES	DESCRIPTION
Inherent deficiency	Inadequate specification Inadequate design
Inherited deficiency	Inherent material defect Improper factory assembly Improper site assembly Improper maintenance Improper repair Improper adjustment
System event	Overload Load removal Over-voltage Resonance Short circuit
External event	Vandalism Impact of external object
Environmental	Lightning High Ambient Low Ambient Rain Water ingress Wind Seismic
Improper application	
Abnormal deterioration	

Table 9: Failure mode classification [Cigré WG A2.18, 2003]

FAILURE MODES	**DESCRIPTION**	
Dielectric	Partial Discharge Tracking Flashover	
Electrical	Open circuit Short circuit Poor joint Poor contact	
Thermal	General overheating Localised hotspot	
Physical chemistry	Contamination	Moisture Particles Gas
	Corrosion	
Mechanical	Bending	
	Breaking Displacement Loosening Vibration	

5.4. FAILURE DATA

Data used for the analysis was from the South African utility, Eskom. Eskom's network is classified into three groups: Generation (Gx), Transmission (Tx) and Distribution (Dx).

The failure database was populated with 382 failures of variously rated transformers occurring in the period 1996 to 2006, out of a total population of 9859 unit-years, as shown in the breakdown of failure data in Table 10 and Table 11. The Gx data consisted only of generator step-up transformers.

Records of the different failure incidents and failure information to populate the database was in the form of failure investigation and repair reports, and information obtained from existing internal failure and asset databases.

Information on the surviving transformers was obtained from asset databases.

Table 10: Breakdown of transformer failure data according to application

TYPE (APPLICATION)	**HIGHEST SYSTEM VOLTAGE [KV]**	**RATED POWER [MVA]**	**NUMBER OF FAILURES**	**POPULATION [UNIT-YEARS]**	**MANUFACTURING PERIOD [YEARS]**
Gx	400 ≥ kV ≥ 275	730 ≥ MVA ≥ 220	47	904	1966 - 1992
Tx	400 ≥ kV ≥ 132	1000 ≥ MVA ≥ 30	262	3963	1960 - 2002
Dx	132 ≥ kV ≥ 66	160 ≥ MVA ≥ 10	73	4992	1961 - 2005

Table 11: Breakdown of transformer failure data according to voltage level and application

APPLICATION	HIGHEST SYSTEM VOLTAGE [KV]	RATED POWER [MVA]	NUMBER OF FAILURES	POPULATION [UNIT-YEARS]	MANUFACTURING PERIOD [YEARS]
Dx	100 > kV ≥ 60	80 ≥ MVA ≥ 10	26	2637	1961 - 2006
Dx, Gx Tx	300 > kV ≥ 100	500 ≥ MVA ≥ 10	207	5001	1960 - 2006
Gx, Tx	700 > kV ≥ 300	1000 ≥ MVA ≥ 40	149	2221	1960 - 2006

5.5. DATA LIMITATIONS

Data was only available for three regions on the Distribution network. The inference drawn from the data could differ from that of the entire Distribution network.

Failure investigation and repair reports could not be located for all the failures. Only 28% of the all the failures had failure reports, as shown in the breakdown of available data in Table 12. As a result, not all the fields in the database could be populated. To avoid the possibility of incorrect population of the database, failures without adequate information were left unclassified.

Table 12: Breakdown of failures with and without reports according to application

APPLICATION	NUMBER OF FAILURES	FAILURES WITH REPORTS	FAILURES WITHOUT REPORTS
Gx	47	28	19
Tx	262	82	180
Dx	73	0	73

Component replacement, in particular bushings and tap changers, was not taken into account due to the lack of information. The age at failure therefore reflects that of the transformer at failure, and not that of the component at failure.

Where the classification into failure locations, failure causes and modes could not be determined, the failure was left unclassified.

Due to the unavailability of data, the distribution failure data could only be classified according to failure location. The transmission and GSU transformer failure data could be classified into all three categories.

As discussed in section 5.1, the definition of failure as used in this study allows for failures with repair, and complete failure. Due to the lack of failure information, no distinction could be drawn between the failure types of the Dx transformers. The group of Dx data therefore consisted of a combination of units in failures with repair, and complete failure. The Tx and Gx data could be classified into failures with repair, and complete failures.

5.6. COMPARING RELIABILITY ACCORDING TO MANUFACTURING PERIOD

Bossi [1983] provided the most complete account of the performance of units from a particular manufacturing period: the pre 1978 build. The South African data will therefore grouped according to manufacturing period, as pre and post 1978 manufactured units, and compared with the results in Bossi [1983]. This comparison with Bossi [1983] will only be limited to the failure rates, and the failures classification.

The South African data will be sorted into a classification (transformer application, voltage and age group) consistent with the classification in Bossi [1983], as follows:

- The definition of failure used in Bossi [1983] requires that the failed transformers be taken out of service for repair, but does not exclude the scrapped transformers.
- Transformers not older than 20 years at failure as per Bossi [1983]
- Highest system voltage from 72kV, and three voltage categories: $60 \leq kV < 100$, $100 \leq kV < 300$ and $300 \leq kV < 700$.
- Because all the South African transformers have on-load tap changers, the results of units with tap changers from Bossi [1983] were used for comparison.
- Bossi [1983] classified transformer application into power station, substation and autotransformers. The South African Distribution and Transmission transformers are all substation transformers consisting of a combination of two winding, three winding and autotransformers. The substation and autotransformers in Bossi [1983] were therefore grouped together for comparison with the combination of Distribution and Transmission transformers.

The classification into failure locations and causes differs in the results in Bossi [1983] and the South African data. To allow comparison of failure locations, the South

African data was re-classified according to Bossi [1983]. The South African failure locations initially classified according to Table 8 were grouped as follows:

- Mechanical structure under the magnetic circuit
- Winding connections and bushings under terminals
- Tank and liquid insulation under tank and dielectric fluid

The failure causes in Bossi [1983] was re-classified according to the South African data as follows:

- Design and manufacture under inherent deficiencies
- Material, incorrect erection on site, and incorrect maintenance under inherited deficiencies
- Abnormal overload, overfluxing and external short circuit under system events
- Transportation or storage under external events

The failure mode classification was very similar between the two.

5.7. IMPACT OF TRANSFORMER SPECIFICATION

In chapter 2, it was identified that changes in the specification could impact on transformer reliability. In chapter 3, the changes in Eskom Distribution's transformer specification were discussed, and it was identified that the impact of changes will only be seen in the failures of transformers manufactured from the early 2000's. From the distribution failure data that was collected, the contribution of transformers manufactured from the 2000's was insignificant. The data is therefore not sufficient to assess the full impact of specification changes. The bushing specification implemented in 2009 across Eskom was also discussed, and due to the data that was collected, the impact of these changes will also only be seen with future studies.

5.8. SUMMARY

In this chapter, the following research questions/aspects were addressed:

1. Applying the recommendations from international standards and guidelines on the treatment of failure data to transformer failures in South Africa.
2. Identifying whether changes in the specification of transformers in South Africa had an impact on reliability.

The extent to which these aspects were addressed is discussed below.

5.8.1. Treatment of Failure Data

Failure was defined, and a database formulated based on the failure reporting form developed in Cigré WG A2.18 [2003]. Failures were also classified into failure locations, causes and modes, in accordance with the classification in Cigré WG A2.18 [2003].

To allow comparison according to manufacturing period (pre and post 1978), the failure causes in Bossi [1983] were re-classified according to Cigré WG A2.18 [2003], and the failure locations of the South African data grouped according to the classification in Bossi [1983].

5.8.2. Impact of Eskom Distribution's Transformer Specification

The available distribution data is not sufficient to assess the full impact of specification changes, and can only be evaluated with future studies. The impact of the bushing specification implemented in 2009 will also be seen in future studies.

5.8.3. Next Steps

In the next chapter, the statistical analysis methods will be assessed for their applicability to the collected transformer data.

CHAPTER 6: THEORY DEVELOPMENT FOR STATISTICAL ANALYSIS OF TRANSFORMER FAILURE DATA

In this chapter, the statistical analysis theory discussed in chapter 4 will be assessed for its applicability to the collected transformer data.

6.1. POPULATION AND SAMPLE

A statistical model describes some population, and to obtain information on the underlying population, a sample is analysed [Nelson, 1982].

In chapter 5, the decision was taken to compare failure rates and the failures classification of pre and post 1978 manufactured transformers. The statistical analysis will therefore also be based on a comparison of these two periods.

The sample of South African data includes the failures that occurred in the period from 1996 to 2006, and all the transformers in operation from the beginning of 1996 until the end of 2006. The manufacturing period of the units spans from 1960 to 2006, and includes pre and post 1978 manufactured units.

The information sought from a population in a certain manufacturing period would be obtained from a sample representative of that population. The samples of pre and post 1978 manufactured transformers would therefore be representative of the populations in those manufacturing periods.

6.2. EXPOSURE MEASUREMENT OF SAMPLE DATA

The sample data consists of all the ages at failure, and ages of units in operation in the period 1996 to 2006.The ages at failure was measured in days from the manufacturing date up to failure date, and expressed in terms of years. Similarly, the age of all transformers in operation was measured in days from the manufacturing date up to the end of each year in the evaluation period, and expressed in terms of years.

The sample data was classified into age intervals given in years as follows: for each age interval t_k , $k = 0,1,2,3...$ the age intervals were defined as:

- For $k = 0$, $t_k = t_0 = 0$
- For $k = 1$, $k - 1 <$ Age $< k$
- For $k > 1$, $k - 1 \leq$ Age $< k$

For the case where $k = 1$, the age interval was defined as 0 < Age < 1 based on the following reasoning:

- It is difficult to define age '0' for a transformer since the transformer consists of many parts and subsystems that are manufactured at different times and consequently are of different ages. Only the assembly of the different parts and subsystems results in the completion of the transformer.
- Age = 0 can also be incorrectly applied. For example, if age is measured in years, then a transformer that was manufactured and failing in the same year, would suggest that its age at failure was 0. However, the age at failure would be the number of months in service, expressed in years. The same reasoning applies operational units in the sample at the end of each year in the evaluation period.
- For the purpose of this study, age = 0 will refer to the completely assembled transformer in the manufacturer's workshop. A test failure in the manufacturer's workshop after assembly would be considered failure at age = 0. Since only in-service transformer failures were considered in service, none of them failed at age = 0. Age = 0 therefore does not form part of the sample.
- This classification is in agreement with the properties of the CDF and reliability functions as discussed in chapter 4, which require that $F(0) = 0$: the failure fraction failing by age = 0 is 0, and $R(0) = 1$: the fraction surviving beyond age = 0. This means that all the transformers in service were in working condition after complete assembly.

6.3. CONTINUOUS DISTRIBUTIONS

Based on the theory in Nelson [1982] and Williams [1991] discussed in chapter 4, the data set (measurements or observations) determines whether a distribution is discrete or continuous.

Discrete data consists of distinct observations or measurement, whereas continuous data is a continuous set of numbers.

Because transformer ages are not distinct and can take on any value, the resulting distribution is continuous. This is demonstrated with an example in Table 13, which gives the ages at failure (in days and years) of 2 units and that of a unit in operation at the end of 2006.

Table 13: Example of transformer ages at failure and operation

TRF NO.	MANUFACTURING DATE	FAILURE DATE	AGE (DAYS)	AGE (YEARS)
1*	1996/01/21	-	4360	11.95
2	1998/03/15	2006/04/21	3688	10.10
3	1978/05/15	1998/05/21	7276	19.93
* Transformer operational at the end of 2006				

6.4. SAMPLE DATA CLASSIFIED INTO DATA TYPES

In chapter 5, it was observed that the definition of failure data allows for failures with repair and complete failures. The evaluation of the nature of the data based on Nelson [1982] and discussed in chapter 4 revealed that when certain groups of data were taken as the sample, they could be treated and classified as either complete data or multiply censored data.

6.4.1. Multiply Censored Data

Multiply censored data consists of failure times intermixed with running times that can result from the removal of units from use before failure or collection of data while units are still running. The running times are referred to as censoring times, and can be left or right censored [Nelson, 1982].

Left and right censoring would apply to a sample containing operational transformers, and transformers in complete failures and failures with repair, as follows:

Failures with Repair: A sample containing operational transformers and units in failures with repair will have left and right censoring times. Because the evaluation period spans from 1996 to 2006, failures with repair prior to 1996 have not been recorded. These would include all the earlier failures with repairs of units manufactured before 1996. The times (ages) at which these units (manufactured prior to 1996) enter the evaluation period in 1996 are referred to as the left censoring times. All the ages of the units surviving (that did not have any failures with repairs in the evaluation period) till the end of 2006 are referred to as the right censoring times.

Complete Failures: A sample containing operational transformers and units in complete failure, will only have right censoring times. Because complete failures were only recorded in the period 1996 to 2006, those units surviving until till the end of 2006 are referred to as the right censoring times.

Assessment of the sample data revealed the following:

a) *Sample consisting of complete failures and survivors* $\Rightarrow$ *Multiply Censored Data:* If the sample is taken to include all the units in complete failure in the period 1996 to 2006 and the units that survived past the end of 2006, then the sample will have failure times, and right censoring times.

b) *Sample consisting of failures with repair and survivors* $\Rightarrow$ *Uncertain:* If the sample is taken to include the units that had failures with repairs and units that survived past the end of 2006, then the sample will have failure times, left censoring and right censoring times. The definition of failure as used in this study allows a transformer to have multiple failures with repair.

c) *Sample consisting of combination of failures with repair, complete failures and survivors* $\Rightarrow$ *Uncertain:* If the sample is taken to cover the definition of failure such that it includes complete failure and failure with repair, and the units that survived past the end of 2006, then the sample will have failure times, left censoring and right censoring times.

In (b) and (c) the samples contain failures with repair, and even multiple failures with repair. Because the theory in Nelson [1982] does not make reference to failures or multiple failures with repair, there is uncertainty in the treatment of such data in this study. Failures with repair will be treated as multiply censored data, but the uncertainty will be acknowledged.

6.4.2. Complete Data

Complete data arises where the failure times of each sample unit is known [Nelson, 1982]. Transformer data treated as complete data therefore does not take into account the surviving transformers. The uncertainties regarding the treatment of failures with repairs, and multiple failures with repair discussed in section 6.4.1 also applies to complete data.

a) *Sample consisting of complete failures* $\Rightarrow$ *Complete Data:* If the sample is selected only to include the complete failures, then the failure times are the times from the year of manufacture to the time of complete failure. The sample can therefore be classified and treated as a complete data set.

b) *Sample consisting of failures with repair* $\Rightarrow$ *Uncertain:* If the sample is selected only to include all the failures with repairs, then each unit can have a number of failures with repair. Consequently, each unit could have a number of failure times to repair. The failure times will be determined from the year of manufacture to the point where each failure with repair occurred.

c) *Sample consisting of the combination of failures with repair and complete failures* $\Rightarrow$ *Uncertain:* For a sample selected only to include the combination of failures with repair and the complete failures, units can have a number of failures with repair, and later complete failures. The failure times would then be a combination of all the failure times to repair, and the failure times to complete failure.

6.5. COMPARING DERIVATION OF PRIMARY CONCEPTS

This section will compare the methodologies for deriving the four primary concepts (from relative frequency) as presented and discussed by Nelson [1982] and Williams [1991].

6.5.1. PDF

Both Nelson [1982] and Williams [1991] use the concept of relative frequency to explain the PDF.

Nelson [1982] defines the probability density $f(y)$ as the mathematical model for the population histogram containing relative frequencies which must be greater than or equal to zero, and sum up to unity, i.e. the properties of PDF. The term relative frequency is not defined by Nelson [1982], but is demonstrated with an example of human mortality based on Edmund Halley's mortality table published in 1693.

Halley's mortality table uses the deaths of humans as the sample data, and counted the number of people for each age up to 84 years [EH, URL1]. The number of deaths was determined by subtracting the number of persons at an age from the number of persons at the previous age. The ages at death were grouped into five year intervals, and the relative frequencies determined per interval. The relative frequency per age interval was determined by dividing number of deaths per interval by the total number of deaths. The resulting relative frequency distribution satisfies the properties of a PDF. The histogram of relative frequencies *roughly corresponds* to a probability density for the population [Nelson, 1982].

In this context, 'roughly corresponding' suggests that the resulting probability is an estimate of the PDF. Statistical analysis of a sample gives information on the population because in most cases a complete population has not failed. The fact that Nelson [1982] describes the PDF as: 'the probability density $f(y)$ as the mathematical model for the population histogram …' implies that if one had the data of the complete population, then the PDF would be representative of the whole population. However, when a sample is used it will be an estimate of the PDF.

The relative frequency distribution is obtained by normalising the frequency of occurrence per interval by dividing it by the total number of occurrences in all intervals [Williams, 1991]. The normalizing of the frequency distribution forces it to have the same properties as described by Nelson [1982]: the relative frequencies must be greater than or equal to zero, and they must sum up to unity. Williams [1991] states that if the number of sample points $n \to \infty$ and the intervals become arbitrarily small, then the relative frequency plot f_k becomes a density function $f_k \to f(x)dx$ (from 4.13).

Despite the generalisation, we need to remember that when working with real data it is impossible to have an infinite number of sample points, and as a result the relative frequency distribution will always estimate the PDF.

Relative frequency as demonstrated by Nelson [1982] is the same as that derived by Williams [1991]. Both arrive at estimates of the PDF which satisfy the required properties of a PDF:

- It must be greater than or equal to zero (since these are all fractions (percentages, probabilities) of the sample).

- It should sum up to unity (all the fractions (percentages, probabilities) must equate to 1 to give the complete sample).

If no theoretical distributions are fitted, then the relative frequency distribution is a non parametric estimate of the PDF.

6.5.2. CDF

In both Nelson [1982] and Williams [1991], the CDF is obtained from the integral of the PDF, which is a summation over the range of the PDF.

In the same way that relative frequency becomes a PDF in Williams [1991], the cumulative relative frequency becomes a CDF as the number of sample points $n \to \infty$ and the intervals become arbitrarily smaller.

Williams [1991] interprets the CDF as the probability of failure between time zero and some non-negative time t. As with Halley's example of human deaths, Williams interprets the CDF as giving the fraction failing by a certain age [Nelson, 1982]. If time t is considered as age then 'between time zero and some non-negative time t implies 'by a certain age', when the interval between age 0 and that 'certain age' is being considered. The two interpretations of the CDF are therefore the same.

In both cases, the properties of the CDF require that equations 4.18 and 4.19, given below, be satisfied.

$$F_i(\infty) = 1 \quad \textit{4.18}$$

$$F_x(-\infty) = 0 \quad \textit{4.19}$$

Equations 4.18 and 4.19 depend on the defined range of the data. Some distributions cannot take negative values. The point is that the statements (equations) here are valid only where the data range is completely unlimited. Neither transformers nor human lives have these properties. The first property therefore describes the effect when the whole sample or population has failed or died, meaning by that time the probability of failure by that age is 1 or 100%. The second property describes the initial conditions when no failure or death has occurred and it has probability zero at that time.

The CDF is an estimate if it is based on a sample from the population, and the CDF is true if the data is that of the whole population. If no theoretical distributions are fitted to the data, then it would be a non-parametric estimate of the CDF.

6.5.3. Survival/Reliability Function

With the example of human mortality, Nelson [1982] interprets reliability as the probability of surviving beyond a certain age. Williams [1991] interprets the reliability function in two ways:

- When one device is put in service at time zero, the probability the device will last more than t units of time is $R(t)$. The probability that the device will fail before t is $1-R(t)$.
- When many of the same devices are all put in service at time zero, the fraction $R(t)$ of them will continue to function after t units of time. Or that a fraction $1-R(t)$ will fail before time t.

In the same way that this two way interpretation applies to a device, it applies to death in humans. The sample survival/reliability function gives the survivorship/reliability of the sample data, from which inference can be drawn on the survivorship/reliability of the population. The two way interpretation would therefore apply to death in humans as follows:

- 1st interpretation: For a person from that population which the sample represents, the survival/reliability function gives the probability that a person from that population will live beyond a certain age.
- 2nd Interpretation: For a group of people of the same age or age interval from that population, the survival/reliability function will give the probability that this group of people will live beyond a certain age.

The probability of death before a certain age or by time t [$1-R(t)$] is given by the CDF, and applies in the same way as described above. Similarly, this two way interpretation can be extended to the PDF and hazard function.

Since the survival/reliability function $R(t)$ can be derived from the CDF as $1-F(t)$, it follows that the survival/reliability function of a life distribution will have the following properties, given by equations 6.1 and 6.2:

$$R(0)=1 \quad \textit{6.1}$$

$$R(\infty)=0 \quad \textit{6.2}$$

The same argument regarding the range of the data as discussed in section 6.5.2 applies to equations 6.1 and 6.2. The first property describes the initial conditions where no failures or deaths have occurred, and the probability of survival is 1. The second property describes the effect when the whole sample or population has failed or died, meaning that none survives past that age and the probability of survival is 0.

6.5.4. Hazard Function

Nelson [1982] describes the hazard function as the instantaneous failure rate at age y, where in the short time Δ from y to $y+\Delta$, a proportion $\Delta \cdot h(y)$ of the population that reached age y fails. Williams [1991] describes the hazard function as the failure rate, which is related to the probability of a device failing within an interval $t < T \leq t+dt$, given that the device is operating properly at time t, t a non-negative integer. Williams [1991] explains this through the concept of relative frequency and the definition of conditional probability.

The two descriptions are the same since:

- In the time interval Δ from y to $y+\Delta$ a proportion fails, which is equivalent to probability of a device failing within an interval $t < T \leq t+dt$.
- The proportion that fails $\Delta \cdot h(y)$ has the condition that age y was reached, which is equivalent to the device operating properly at time t.
- Both describe the hazard function in terms of the reliability function and the PDF.

6.6. APPLICATION OF PRIMARY CONCEPTS TO DATA TYPES

The PDF and CDF were derived from relative frequency. Relative frequency applies to complete data since it does not take the surviving population into consideration. The derivation of the concepts could therefore also be extended to multiply censored data, and will be demonstrated in this section.

6.6.1. Complete Data

A sample with complete data will consist of all the failure times of the items in the sample.

Halley's mortality table in Nelson [1982] is an example of complete data where the ages at death (in this application: failure times) were grouped into 5 year intervals. The PDF, CDF, reliability function and hazard function in Halley's mortality table were determined as follows:

a) **PDF**: $f(t)$

$$f(t) \rightarrow f_k = \frac{n_k}{n} \qquad 4.1$$

Where:

$k =$ Interval index

$n_k =$ Number of failures in an interval

$n =$ Total number of failures across all the intervals

$f_k =$ Relative frequency of an interval

b) **CDF**: $F(t)$ from equation 4.2:

$$F(t) \rightarrow N_k = \sum_{i=1}^{k} n_i \qquad 4.2$$

Where:

$k =$ Interval index

$n_i =$ Frequency of an interval

$N_k =$ Cumulative frequency of an interval

c) **Survival/Reliability Function**: $R(t)$

$$R(t) = 1 - F(t) \qquad 4.30$$

d) **Hazard Function**: $h(t)$

$$h(t) = \frac{f(t)}{R(t)} \qquad 4.32$$

The hazard function $h(t)$, was then divided by the width of the interval, which in the case of the example in Nelson [1982], was 5 years.

6.6.2. Multiply Censored Data

The derivation of the four concepts using relative frequency could be extended to multiply censored data consisting of the failure times and running times of units, based on the following reasoning.

Hazard Function: From Williams [1991], the hazard function is related to the probability of a device failing within an interval $(t, t + dt)$ given that the device is operating properly at time t. This relationship was simplified using equations 4.34, 4.35, and 4.36 to give the hazard function as:

$$h(t) = \frac{1}{n(t)} \frac{dn}{dt} = \frac{f(t)}{R(t)} \qquad 4.37$$

Where:

$n(t) =$ number of devices that are operating properly at time t

$dn =$ number that fail in the interval between t and $t + dt$

$dt =$ width of the interval

In this study, the sample data was classified into age intervals given in years as follows: for each age interval t_k , k = 0, 1, 2, 3 … the age intervals were defined as $k-1$ < Age < k for $k = 1$, and $k > 1$ as $k-1 \leq$ Age < k. This is demonstrated with an arbitrary example in Table 14.

Table 14: Transformers failures and units in operation with age intervals

Interval No. (tk)	Age Interval	Units in Operation	Failures
2	$2 \leq$ Age < 3	59	2
4	$4 \leq$ Age < 5	60	2
5	$5 \leq$ Age < 6	67	3
8	$8 \leq$ Age < 9	83	1

Table 14 gives the total number of failures and number of units in operation per age intervals over the period 1996 to 2006. This means that in interval 2 there were a total of 59 transformers with age in the interval $2 \leq$ Age < 3, in operation from 1996 to 2006. During this period, 2 transformers with age in the interval $2 \leq$ Age < 3 failed. Here t would be 2 and dt the time from 2 to just before 3.

In terms of the example in Table 14, $n(t)$ would be given by column 3: units in operation, and dn by column 4: failures. With the width of the interval, dt, being 1, and using equation 4.37, the hazard function becomes:

$$h(t) = \frac{dn}{n(t)} \qquad 6.3$$

Survival/Reliability Function: In equation 4.29, Williams [1991] defined the CDF as:

$$F(t) = P(T \leq t) = P(0 \leq T \leq t) = \int_0^t f(\tau)d\tau \qquad 4.29$$

This can be written in terms of the reliability function as:

$$R(t) = 1 - F(t) \qquad 4.30$$

$$R(t) = 1 - \int_0^t f(\tau)d\tau \qquad 4.31$$

Expanding this equation yields the reliability function in terms of the hazard function:

$$R(t) = 1 - \int_0^t f(\tau)d\tau$$

$$\frac{d}{dt}R(t) = \frac{d}{dt}(1 - \int_0^t f(\tau)d\tau)$$

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

$$\frac{d}{dt}R(t) = -R(t)h(t)$$

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

$$h(t) = -\frac{d}{dt}\ln R(t)$$

$$\int_0^t h(t)dt = -\ln R(t)$$

$$R(t) = e^{-\int_0^t h(t)dt} \qquad 6.4$$

CDF*:* Using equation 4.30, the CDF can be derived from the reliability function as:

$$F(t) = 1 - R(t) \qquad 6.5$$

PDF: The properties of the CDF require that for the initial conditions at age = 0, all transformers are operational. It also requires that the CDF is 1 at age where all the transformers have failed, i.e. $F(t_0) = F(0) = 0$. For $k = 0,1,2,3,...$ the PDF per interval t may be determined as follows:

$$f(t_k) = F(t_k) - F(t_{k-1}) \qquad 6.6$$

6.7. FAILURE RATE AND INSTANTANEOUS FAILURE RATE

The hazard function gives the *instantaneous failure rate* with time [Nelson, 1982, Tobias, 1986, Elerath, 2000, IEC, 1990]. A condition in IEC [1990] requires that only the failures of non-repaired items be considered when using the expression for instantaneous failure rate. According to IEC [1990], a non-repaired item is an item which is not repaired after failure.

The *average failure rate* over an interval can then be determined from the integral of the hazard function over that interval, divided by the width of the interval [Tobias, 1986, Elerath, 2000, IEC, 1990].

Elerath [2000] further distinguished between annual failure rate and annualised failure rate. The *annual failure rate* is similar to the average failure rate but the interval is one year. The *annualised failure rate* is an estimate of the annual failure rate based on extrapolating beyond the period of time that data was collected, and normalising to one year.

Bossi [1983], IEEE [1986], and Kachler [2001] all use the term failure rate and the definitions are dedicated to transformers. Although the denominators of these definitions are phrased differently, they are all the same. The following example demonstrates that the number of accumulated service years over a period of time is equivalent to the number of transformers in service over a period of time. Consider an arbitrary example of 232 transformers in service over the period 1996 to 2005, as shown in Table 15. The accumulated service years per transformer in that ten year period is shown in Table 16. Both the total number of service years accumulated and the number of transformers in service equate to 232 over the period. With 12 transformers in service in 1996, each transformer accumulated 10 service years in the period. In 1997, 8 transformers were added, each accumulating 9 service years in the period. And in 1998, an additional 5 were added, each accumulating 8 years.

Table 15: Number of transformers-years in service in the period 1996 to 2005

Year	**No. of Transformers in Service**
1996	12
1997	20
1998	25
1999	25
2000	25
2001	25
2002	25
2003	25
2004	25
2005	25
Total	**232**

Table 16: Number of accumulated service years in the period 1996 to 2005

Transformer No.	**Accumulated Service Years Per Transformer**
1	10
2	10
3	10
4	10
5	10
6	10
7	10
8	10
9	10
10	10
11	10
12	10
13	9
14	9
15	9
16	9
17	9
18	9
19	9
20	9
21	8
22	8
23	8
24	8
25	8
Total	**232**

IEEE [1986] and Kachler [2001] expressed the numerator of the failure rate definition in terms of forced outages only, whereas Bossi [1983] calculated failure rate for scheduled and forced outages. Both Bossi [1983] and IEEE [1986] require the immediate removal of the transformer from service. Bossi [1983] also requires that the removal from service take place within 30 minutes. The definitions of scheduled outage and defect in both references are the same. Failures with scheduled outages occur when a transformer is deliberately taken out of service at a selected time. Defects arise where imperfection or the lack of performance may be corrected or eliminated without taking the transformer out of service.

According to IEEE [1986], there is a difference between reliability measurement and reliability improvement. Failures with scheduled outages should not be used to determine the failure rate statistic which is a form of reliability measurement. Failures with scheduled outages and defects should be pursued from a reliability improvement perspective.

Based on the classification in Elerath [2000], the failure rate as determined in Bossi [1983], Kachler [2001] and IEEE [1986] is an *average annual failure rate*, taken over a number of years, instead of one year.

Based on the aforementioned discussions on the failure rate terms, the following shall apply:

- *Instantaneous failure rate* is determined from the hazard function. The South African data consists of failures with repair, and complete failures, as discussed in chapter 5. The constraint in IEC [1990] regarding the use of the instantaneous failure rate with repaired items discussed earlier in this section is, however, acknowledged.
- *Average failure rate* over an interval is determined from the integral of the hazard function over the interval, divided by the width of the interval.
- *Average annual failure rate* is determined as the ratio of the number of transformer failures over a period, to the number of transformers in service in the same period. The results in Bossi [1983] are the most reliable source in the transformer industry, and present failure rates for failures in both forced and scheduled outages. Because these statistics will be used in the comparison of annual failure rates between manufacturing periods, the annual failure rate will be determined for failures in forced and scheduled outages. The constraint in IEEE [1986] regarding the use of the annual average failure rate with outage type discussed earlier in this section is, however, acknowledged.

6.8. NON PARAMETRIC ANALYSIS OF TRANSFORMER FAILURE DATA

The aim of the analysis is to obtain the four primary concepts from which statistical inference can be drawn. Based on the population and sample of transformer failure data, two data types were identified: complete data and multiply censored data.

In chapter 4, non parametric plotting methods for analysing data these data types were identified and described as:

- Probability Plotting $\Rightarrow$ produces a sample CDF and reliability function
- Hazard Plotting $\Rightarrow$ produces a hazard function

Further, in section 6.6 it was shown how the four concepts derived from relative frequency could be applied to complete and multiply censored data. If no theoretical distribution is fitted to the data, the resulting distributions are by definition non parametric estimates.

This section will discuss non parametric analysis of transformer data based on these two approaches: plotting techniques and derivation from relative frequency.

The age interval classification of the sample data discussed in section 6.2 will be used throughout.

The interpretation of the hazard function will be extended to apply to the transformer data.

6.8.1. Complete Data

The statistical analysis and inference drawn from complete data is based on a sample consisting only of the failures, omitting the effects of the surviving transformers.

6.8.1.1. Primary Concepts from Relative Frequency

PDF: The relative frequency distribution determined from the number of failures (frequency) per age interval t_k, and normalized by dividing it by the total number of failures, gives the relative frequency distribution. The relative frequency distribution is the non parametric estimate of the PDF. The properties of the PDF require that all the points of the PDF are less than or equal to 0, and their sum equate to 1. The PDF may be interpreted as follows:

- For a transformer from the specified population of interest which the sample data represents, the PDF gives the probability of failure at a certain age.
- For a group of transformers of the same age from the specified population which the sample data represents, the PDF will give the probability of failure at a certain age.

CDF: The cumulative sum of the PDF per age interval gives the CDF. The resulting CDF is a non parametric estimate of the CDF. The properties of the CDF require that for the initial conditions at $t_0 = 0$ (age = 0), all transformers are operational. It also requires that the CDF is 1 at age where all the transformers have failed. The CDF may be interpreted as follows:

- For a transformer from the specified population which the sample data represents, the CDF gives the probability that the transformer will fail by a certain age.
- For a group of transformers of the same age from the specified population which the sample data represents, the CDF gives the probability that this group of transformers will fail by a certain age.

Survival/Reliability Function: The reliability function values per age interval t_k will be determined from $R(t_k) = 1 - F(t_k)$, as the non parametric estimate of the reliability function. Because the reliability function is determined from the CDF, its properties follow from the properties of the CDF:

- For the initial conditions at $t_0 = 0$ (age = 0) it has a probability of survivorship of 1.
- Probability of survivorship is 0 by the age that all the transformers have failed.

The reliability function may be interpreted as follows:

- For a transformer from the specified population which the sample data represents, the reliability function gives the probability that the transformer will last beyond a certain age.
- For a group of transformers of the same age from the specified population which the sample data represents, the reliability function will give the probability that this group of transformers will live beyond a certain age.

Hazard Function: The hazard function will be determined from the PDF and reliability function, resulting in a non parametric estimate of the hazard function.

The hazard function may be interpreted as follows:

- For a transformer from the specified population which the sample data represents, the hazard function gives the instantaneous failure rate at a certain age.

- For a group of transformers of the same age from the specified population which the sample data represents, the hazard function gives the instantaneous failure rate at a certain age.
- Inference on the nature of the instantaneous failure rate with age will be based on the shape of the hazard function.

As discussed in chapter 4, the shape of the hazard function can further be used to give the following interpretation of equipment or product life:

- Decreasing: Should this decrease be evident during early life of a product or equipment, it indicates design and manufacturing related problems.
- Constant: When flaws leading to early life failures no longer appear, the product or equipment goes into a steady state.
- Increasing: An increasing hazard function during later life of a product is said to correspond to wear-out failure. Such failure rate behaviour often indicates that failures are due to the product wearing out.

Although illustrated in this way, the trends can change at any period in the life of a product or equipment, for example in these two scenarios:

- A decrease of failures occurring in later life could suggest that the reliability of the product improves, for instance with products that have been repaired and show an improved performance.
- An increase in mid life could suggest that design related problems not understood at the time of design or manufacture, are surfacing later in life.

The interpretation of the hazard function periods using the transformer data would typically be representative of the following failure causes identified in chapter 5:

- Higher failure rates in early life: Inherent deficiencies. Can also manifest itself later in life.
- Constant/low failure rates: Inherited deficiencies, system and external events, abnormal deterioration, environmental factors.
- Increasing failure rates: Abnormal deterioration, aging, system events.

6.8.1.2. CDF and Reliability Function from Probability Plotting

The sample CDF will be constructed as follows:

1. For a total of n failures, order the n failure times from smallest to largest. Failure times will be ordered in terms of the age interval classification t_k. Where multiple failures occurred per age interval, the failure times will be listed successively. For example, if 5 transformers failed in particular age interval, then each of the 5 will be listed successively.
2. Assign a rank to each failure. Give the earliest rank 1, the second failure rank 2 etc., and the last failure has rank n.
3. Calculate the probability plotting positions F_i. For the failure with rank i, the midpoint plotting position is:

$$F_i = \left(\frac{i - 0.5}{n} \right) \quad , \; i = 1, \ldots, n \qquad 6.7$$

4. Probability plotting positions can also be calculated as:

$$F_i = \left(\frac{i}{n} \right) \quad , \; i = 1, \ldots, n \qquad 6.8$$

5. Obtain the sample reliability function as:

$$R_i = 1 - F_i \quad , \; i = 1, \ldots, n \qquad 6.9$$

6. Plot and interpret the CDF and reliability function as discussed in section 6.8.1.1.

6.8.1.3. Hazard Function from Hazard Plotting

The sample hazard function is constructed as follows:

1. For a total of n failures, order the n failure times from smallest to largest.
2. Order the failure times from smallest to largest. Failure times will be ordered in terms of the age interval classification t_k.
3. Where multiple failures occurred per age interval, the failure times will be listed successively. For example, if 5 transformers failed in a particular age interval, then each of the 5 will be listed successively.

4. Label the times with reverse ranks; label the first time with n, the second $n-1$, etc. and the n^{th} with 1.
5. Calculate the hazard value for each failure time as $100/j$ where j is its reverse rank.
6. Calculate the cumulative hazard value as the sum of its hazard value, and the cumulative hazard value of the preceding failure.

6.8.2. Multiply Censored Data

The statistical analysis and inference drawn from multiply censored data will be based on a sample consisting of the failures and the surviving transformers. The interpretation of each of the concepts as discussed in section 6.8.1 applies.

6.8.2.1. Primary Concepts from Relative Frequency

The operational transformers being used are those that are operating at the end of each year in the evaluation period.

Hazard Function: Non parametric estimate of the hazard function is determined per age interval t_k from the ratio of the number of transformer failures per interval dn, to the number of transformers operating properly per interval $n(t_k)$. Expressed as follows:

$$h(t_k) = \frac{dn}{n(t_k)} \qquad 6.10$$

Reliability Function: Non parametric estimate of the reliability function determined per age interval t from the hazard function using the relationship:

$$R(t_k) = e^{-\int_0^{t_k} h(t_k)dt} \qquad 6.4$$

CDF: Determined per age interval t_k from $F(t_k) = 1 - R(t_k)$, as the non parametric estimate of the CDF.

PDF: The properties of the CDF require that for the initial conditions at age = 0, all transformers are operational. It also requires that the CDF is 1 at age where all the transformers have failed, i.e. $F(t_0) = F(0) = 0$. For $k = 0,1,2,3,...$ the PDF per interval t may be interpreted as follows:

$$f(t_k) = F(y_k) - F(t_{k-1}) \qquad 6.11$$

6.8.2.2. CDF and Reliability Function from Probability Plotting

Three methods were discussed in chapter 4 for probability plotting of multiply censored data: Herd-Johnson method, Kaplan-Meier method, and the actuarial method. The actuarial method was recommended for larger samples. The samples of transformers discussed in chapter 5 were adequate to be considered as a large sample.

The sample consisting of the failures and the operational transformers can be considered as a large sample. The operational transformers that will be used are the ones in operation at the end of the evaluation period. The actuarial probability plotting method will be applied as follows:

1. Assign age intervals t_k.
2. For each interval determine the number of units that enter r_k, the number that fail f_k, and the number that are censored c_k.
3. Determine r_{k+1} as $r_{k+1} = r_k - f_k - c_k$.
4. The sample reliability function estimate is calculated as:

   $$R(t_k) = 1 - \left[\frac{f_k}{(r_k - 0.5c_k)} \right] \qquad 6.12$$

   Where $R(t_0) = R(0) = 1$. The $-0.5c_k$ adjusts for the censored units, which are assumed to run about half the interval.
5. The sample CDF can be derived from the reliability function as:

   $$F(t_k) = 1 - R(t_k) \qquad 6.13$$

6.8.2.3. Hazard Function from Hazard Plotting

Except for the inclusion of the running times of the operational units, hazard plotting of complete and multiply censored data is the same. The hazard and cumulative hazard functions are obtained as follows:

1. Order the n running (censoring) times and failure times from smallest to largest, without regard to which is a censoring or failure time. Failure times will be ordered in terms of the age interval classification t_k. Where multiple failures occurred per age interval, the failure times will be listed successively.
2. Label the times with reverse ranks; label the first time with n, the second, $n-1$ etc. and the n^{th} with 1.
3. Mark running times.
4. Calculate the hazard value for each failure time as $100/j$ where j is its reverse rank.
5. Calculate the cumulative hazard value as the sum of its hazard value, and the cumulative hazard value of the preceding failure.

6.9. SUMMARY

This chapter assessed the applicability of the statistical analysis methods discussed in chapter 4, to the collected transformer data. The extent to which this has been assessed, additional aspects identified, and next steps are discussed below.

6.9.1. Identified Data Types

The transformer data was classified into two data types: complete data and multiply censored data, and it was further identified that the transformer data was representative of a continuous distribution.

6.9.2. Failure Types and Uncertainties in Statistical Analysis

The samples contain failures with repair, and even multiple failures with repair. Because the theory in Nelson [1982] does not make reference to failures with repair or multiple failures with repair, there is uncertainty in the treatment of such data in this study. Failures with repair will be treated as multiply censored data, but the uncertainty will be acknowledged.

6.9.3. Application of Primary Concepts

The derivation and interpretation of the four primary concepts as applied to continuous distributions from two literature sources were compared, and it was found that they were similar.

The primary concepts were derived from relative frequency which applies to complete data, since it does not take the surviving transformers into consideration. The relative frequency method was further extended for application to multiply censored data.

6.9.4. Extending Interpretation of the Hazard Function

The hazard function interpretation was extended to the collected transformer data, and would typically be representative of the following failure causes identified in chapter 5:

- Higher failures rates: Inherent deficiencies. Can also manifest later in life.
- Constant/Low failure rates: Inherited deficiencies, system and external events, abnormal deterioration, environmental factors.
- Increasing periods: Abnormal deterioration, aging, system events.

6.9.5. Non Parametric Analysis Methods

Non parametric analysis of the two data types using plotting techniques (probability plotting and hazard plotting) from the primary concepts was discussed in the context of transformer data. It was further shown that the relative frequency method could be considered as a non parametric technique since no mathematical distribution is fitted to it. The limitations of non parametric techniques were also discussed, and acknowledged.

6.9.6. Types of Failure Rate

Three types of failure rate were distinguished: instantaneous failure rate, average failure rate, and average annual failure rate.

6.9.7. Next Steps

Based on the aforementioned discussions, the next chapter will present the analyses of the South African failure data in terms of the following:

6.9.7.1. Annual Average Failure Rates

Determining the average annual failure rates of post 1978 manufactured transformers failures, and comparing them with the results of pre 1978 manufactured transformers in Bossi [1983].

6.9.7.2. Failures Classification

Classification of post 1978 manufactured transformer failures into failure locations, failure causes, and failure modes according to transformer application, and comparison with the results of pre 1978 manufactured transformers in Bossi [1983].

The pre 1978 results from Bossi [1983] were presented and discussed in the literature review of chapter 2. Since the average annual failure rate and failures classification was based on a comparison of pre and post 1978 manufactured transformers, the pre 1978 results will be given in this chapter again for completeness sake and to allow comparison.

6.9.7.3. Validating the Applicability/Relevance of the Statistical Analysis

This chapter assessed the applicability of the statistical analysis methods to transformer data. The uncertainty around the treatment of the transformer failure data was discussed, and the hazard function interpretation extended to the transformer data.

The two non parametric approaches used for determining the primary concepts from both data types will be applied to pre and post 1978 manufactured transformer failure data from South Africa, to validate the applicability of the theory.

The validation will be based on observing whether there is agreement between the actual hazard function interpretation and the expected hazard function interpretation for transformer data. If there is agreement, inference will be drawn on the reliability according to manufacturing period, based on the major contributors of failure (failure locations, causes and modes).

CHAPTER 7: RESULTS OF DATA ANALYSIS

7.1. AVERAGE ANNUAL FAILURE RATE (AAFR) ACCORDING TO MANUFACTURING PERIOD

7.1.1. According to Application and Voltage Groups

At 3.0% and 2.8%, AAFRs of pre and post 1978 manufactured transformers with tap changers were very similar (Table 17). The AAFR of post 1978 units was almost 1% higher than the industry benchmark of 2% determined in Bossi [1983]. The industry benchmark applied to transformers with and without a tap changer (Table 18).

Significant differences of up to 1.5% were observed in the breakdown into transformer application. AAFRs of post 1978 manufactured power station transformers (GSUs) were higher than pre 1978 units, and those of pre 1978 substation and autotransformers were higher than post 1978 units.

Significant differences exceeding 1% were also observed in comparison by transformer application and voltage category, in particular in units from 100kV. A 4% change occurred in power station transformers in the 100kV to 300kV voltage category where the AAFR of post 1978 manufactured units was higher than pre 1978 units. The AAFR of post 1978 manufactured substation and autotransformers in this voltage category was also higher than that of pre 1978 units.

Differences of less than 1% were observed in the comparison by voltage category and manufacturing period. There was no data available for power station transformers in the 60kV to 100kV voltage range, which makes the comparison in this voltage category only possible with substation and autotransformers. However, the AAFR with voltage category in each manufacturing period indicated that it increased with increasing system voltage in units from both manufacturing periods.

Table 17: Comparison of AAFRs according to manufacturing period, transformer application and highest system voltage for transformers with tap changers

APPLICATION & VOLTAGE GROUPS	PRE 1978 [1]			POST 1978 [2]		
	Unit-Years	Failures	Failure Rate	Unit-Years	Failures	Failure Rate
60 ≤ kV < 100	**1097**	**17**	**1.5%**	**753**	**2**	**0.3%**
Power Station TRFS	840	15	1.8%	-	-	-
Substation & Auto TRFS	257	2	0.8%	753	2	0.3%
100 ≤ kV < 300	**3719**	**82**	**2.2%**	**2687**	**69**	**2.6%**
Power Station TRFS	2559	65	2.5%	77	5	6.5%
Substation & Auto TRFS	1160	17	1.5%	2610	64	2.5%
300 ≤ kV < 700	**2186**	**113**	**5.2%**	**1247**	**60**	**4.8%**
Power Station TRFS	748	18	2.4%	388	13	3.4%
Substation & Auto TRFS	1438	95	6.6%	859	47	5.5%
60 ≤ kV < 700	**7002**	**212**	**3.0%**	**4687**	**131**	**2.8%**
Power Station TRFS	4147	98	2.4%	465	18	3.9%
Substation & Auto TRFS	2855	114	4.0%	4222	113	2.7%
[1] Bossi [1983], [2] South African Data						

7.1.2. According to Voltage and Age Groups

Bossi's AAFR with age group did not distinguish between units with or without on-load tap changer, or transformer application (Table 18). The post 1978 manufactured units were all fitted with tap changers.

Differences of less than 1% were observed with age group in both pre and post 1978 manufactured transformers. The AAFR could therefore be considered as relatively constant with increasing age group, in both manufacturing periods.

Significant differences exceeding 1% were observed in the first 5 years in the 100kV to 300kV, and 300kV to 700kV range (the most significant at 4.5%); and in midlife from 10 to 20 years of the combined group (60kV to 700kV) and those in the 300kV to 700kV range. In each of these cases AAFRs of post 1978 manufactured transformers were higher than pre 1978 units.

Table 18: Comparison of AAFRs according to manufacturing period, system voltage and age groups for transformers with and without tap changers

VOLTAGE & AGE GROUPS	PRE 1978 [1]			POST 1978 [2]		
	Unit-Years	Failures	Failure Rate	Unit-Years	Failures	Failure Rate
60 ≤ kV < 100	**15868**	**322**	**2.0%**	**-**	**-**	**-**
0 < Age ≤ 5	3444	96	2.8%	122	0	0.0%
5 < Age ≤ 10	3891	80	2.1%	230	1	0.4%
10 < Age ≤ 20	8533	146	1.7%	401	1	0.2%
100 ≤ kV < 300	**24967**	**490**	**2.0%**	**-**	**-**	**-**
0 < Age ≤ 5	7798	131	1.7%	585	17	2.9%
5 < Age ≤ 10	7471	143	1.9%	654	9	1.4%
10 < Age ≤ 20	9698	216	2.2%	1448	43	3.0%
300 ≤ kV < 700	**6234**	**148**	**2.4%**	**-**	**-**	**-**
0 < Age ≤ 5	2912	56	1.9%	257	6	2.3%
5 < Age ≤ 10	2055	52	2.5%	272	19	7.0%
10 < Age ≤ 20	1267	40	3.2%	718	35	4.9%
60 ≤ kV < 700	**47069**	**960**	**2.0%**	**-**	**-**	**-**
0 < Age ≤ 5	14154	283	2.0%	964	23	2.4%
5 < Age ≤ 10	13417	275	2.0%	1156	29	2.5%
10 < Age ≤ 20	19498	402	2.1%	2567	79	3.1%
[1] Bossi [1983], [2] South African Data						

7.2. FAILURE LOCATIONS

7.2.1. Substation and Autotransformers

In pre 1978 manufactured units, the three major contributors to failure were windings, other accessories and the tap changer (Figure 18). Post 1978 manufactured units featured terminal, tap changer and winding related failures as major contributors (Figure 18).

Winding and tap changer related failures were among the major contributors, irrespective of manufacturing period. Terminals were a major contributor in post 1978 manufactured units, but not in pre 1978. Other accessories were a major contributor in pre

1978 manufactured units, but not in post 1978 manufactured units. Failures developing in the magnetic circuit were a minor contributor in units from both manufacturing periods.

The **terminal** related failures in post 1978 manufactured transformers were predominantly bushing related. The distribution transformers with bushing failures had their onset at 4 years, and transmission transformers failures from 7 years.

Post 1978 manufactured distribution transformers with **winding** related failures were concentrated in the first 10 years, with one manufacturer contributing to the majority of these failures. These units were mostly in the 100kV to 300kV voltage range. Failures above 10 years occurred predominantly in the Eastern region.

In transmission transformers, winding related failures were concentrated in the age group above 10 years, and the failures occurred predominantly in the North Eastern grid of the transmission network.

Tap changer related failures in post 1978 manufactured transmission transformers occurring in the first 10 years were from one manufacturer.

In post 1978 units, failures related to **other accessories** were predominantly due to problems originating in radiators and fans of the cooling system. These failures mostly occurred in larger transmission units of rated power from 500MVA in the 300kV to 700kV voltage range, and had their onset from 2 years.

Bossi [1983] did not describe what was included under other accessories; however it will be assumed that this included the cooling system.

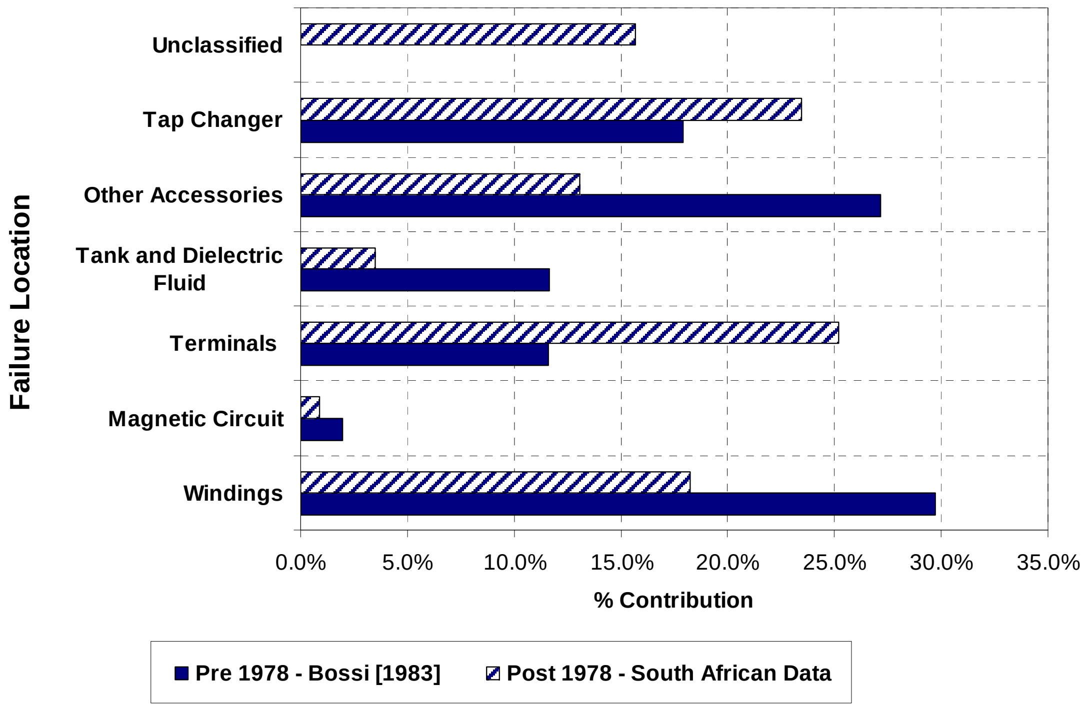


Figure 18: Failure locations in pre and post 1978 manufactured substation and autotransformers

7.2.2. Power Station Transformers

Power station transformer failures were mostly winding and terminal related in units from both manufacturing periods (Figure 19). The contribution of both failure locations was higher in post 1978 manufactured units.

The post 1978 sample were all GSUs, and the classification under **terminals** included the winding connections (winding exit leads and tapping winding exit leads) and bushings. The sample of terminal related failures consisted predominantly of those developing in the winding connections.

Tap changer related failures were a minor contributor in units from both manufacturing periods.

Post 1978 manufactured transformers did not feature any failures related to the magnetic circuit, other accessories, or the tank and dielectric fluid. Failures originating in the magnetic circuit were a minor contributor in pre 1978 manufactured units.

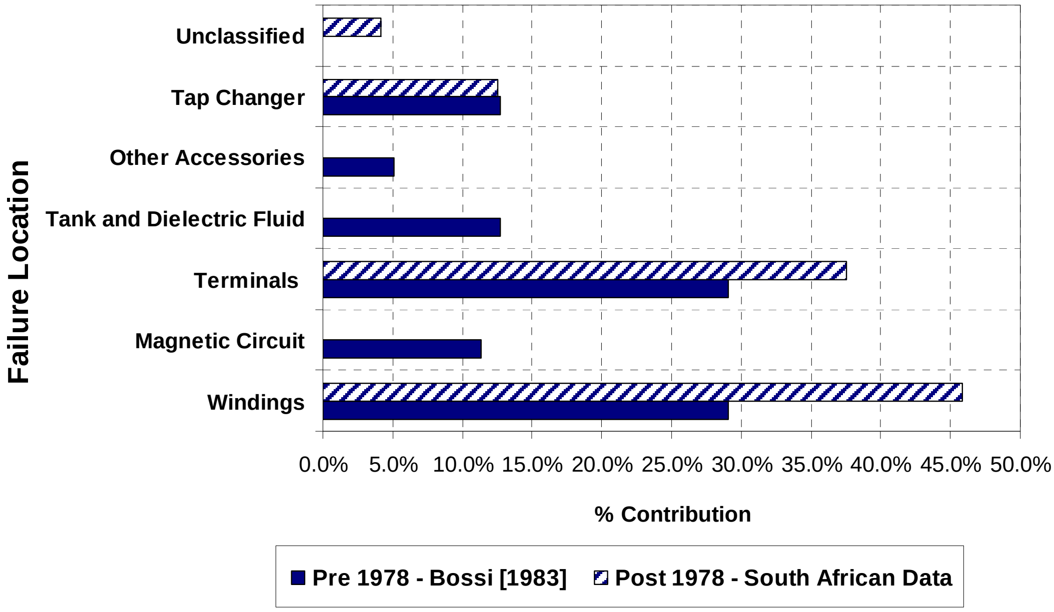


Figure 19: Failure locations in pre and post 1978 manufactured power station transformers

7.3. FAILURE CAUSES

The pre 1978 results contained no detail on the failure causes in the specific failure locations. Only the post 1978 sample for which failure causes were available will be discussed.

7.3.1. Substation and Power Transformers

In pre 1978 manufactured transformers, inherent and inherited deficiencies were the largest contributors of failure causes (Figure 20). In post 1978 manufactured units, inherited deficiencies, abnormal deterioration and inherent deficiencies were the largest contributors (Figure 20).

Pre 1978 manufactured units featured no failures due to abnormal deterioration, external events or improper application (Figure 20).

From section 7.2.1, the major contributors of failure locations in post 1978 manufactured units were terminals (predominantly bushings), tap changers and windings.

Bushing related failures in transmission transformers were due to abnormal deterioration, and inherent (inadequate design or manufacturing) and inherited deficiencies (improper maintenance and improper factory assembly). Abnormal deterioration and inherited deficiencies featured in units from 9 years, and inherent deficiencies from 7 years. The distribution transformers had no failure cause classification, but the majority occurred in the Eastern region on the distribution network.

Tap changer related failures in transmission transformers were mostly due to inherited (improper maintenance, repair and factory assembly) and inherent deficiencies (design and manufacturing), which had their onset from 4 years.

The winding related failures in post 1978 manufactured transmission transformers were due to system events, abnormal deterioration and inherited deficiencies, with failures having their onset from 3 years.

Failures developing in the cooling system were due to maintenance related inherited deficiencies.

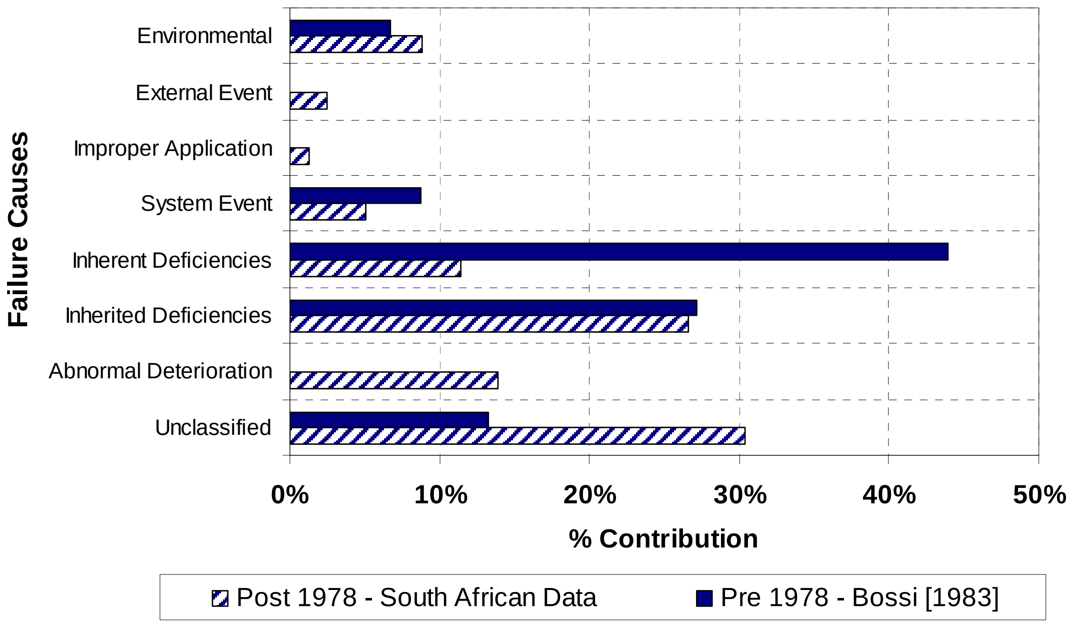


Figure 20: Comparison of failure causes in pre and post 1978 manufactured substation and autotransformers

7.3.2. Power Station Transformers

In pre 1978 manufactured transformers, inherent deficiencies contributed to the majority of the failure causes, followed by inherited deficiencies. Post 1978 manufactured unit failures were mostly due to system events, inherent deficiencies and abnormal deterioration. They were also the major contributors of winding and terminal related failures.

Failures developing in the terminals (winding connections) and windings occurred in units from 14 years, and were predominantly from one manufacturer. This could be attributed to inherent deficiencies of the particular manufacturer's design or manufacturing process.

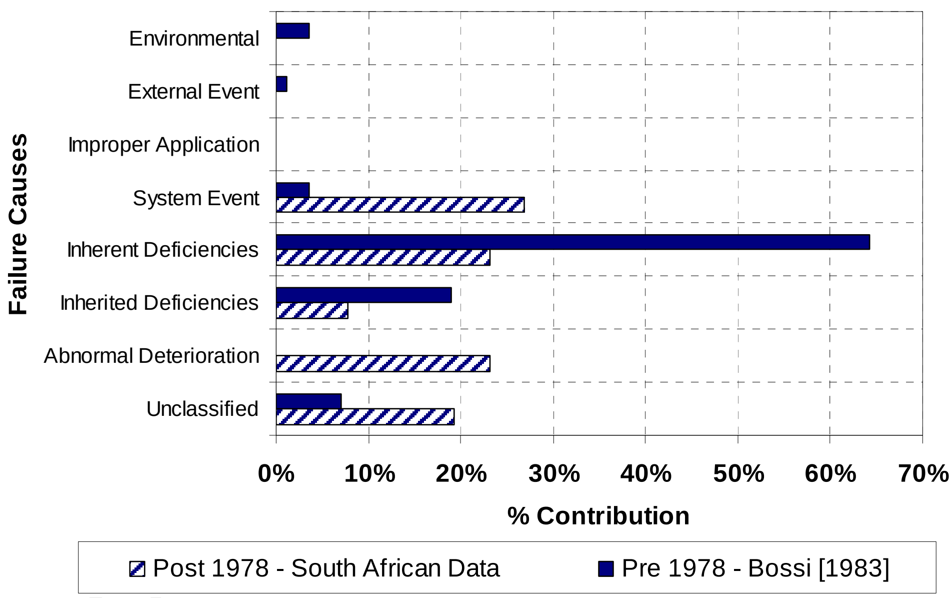


Figure 21: Comparison of failure causes in pre and post 1978 manufactured power station transformers

7.4. FAILURE MODES

7.4.1. Substation and Autotransformers

Dielectric and mechanical mode failures were the largest contributors of failure modes in units from both manufacturing periods (Figure 22). These failure modes were also the largest contributors in bushings, tap changer and winding related failures of post 1978 manufactured transmission transformers. Failures in the cooling system were predominantly of the mechanical mode.

Post 1978 manufactured units did not feature any thermal mode failures. Pre 1978 manufactured units did not feature any physical chemistry or electrical mode failures.

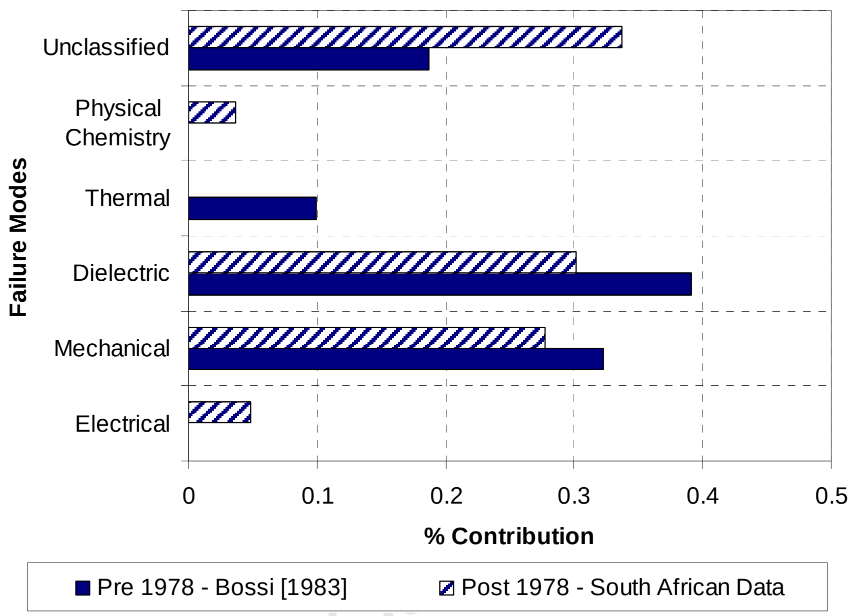


Figure 22: Comparison of failure modes in pre and post 1978 manufactured substation and autotransformers

7.4.2. Power Station Transformers

Thermal and mechanical mode failures were among the major contributors, irrespective of manufacturing period (Figure 23). In pre 1978 manufactured power station transformers, dielectric, thermal and mechanical mode failures were the largest contributors. In post 1978 manufactured units, thermal, mechanical and electrical type failures were the largest contributors. The winding and terminal related failures were predominantly thermal mode failures.

Pre 1978 manufactured units featured no electrical type failures, while post 1978 manufactured units had no physical chemistry related failures.

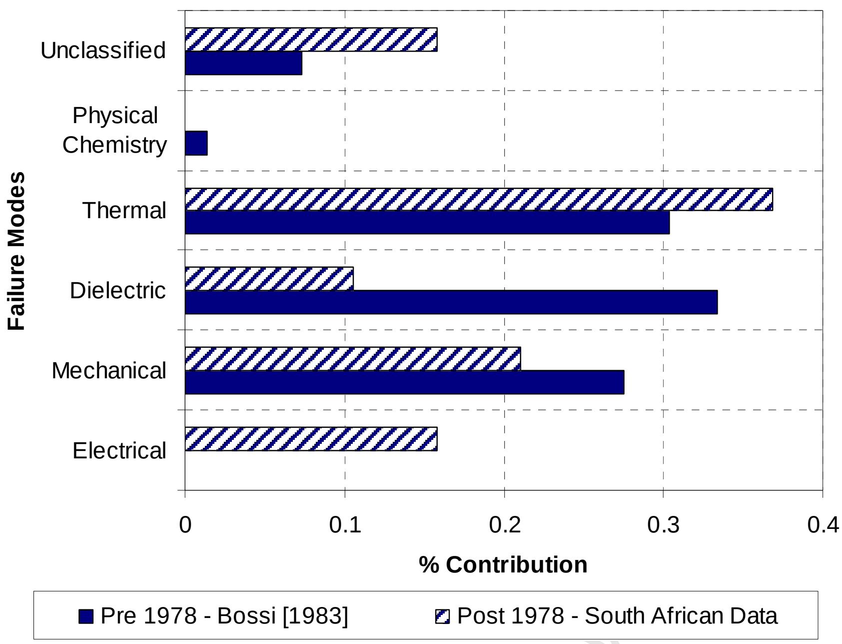


Figure 23: Comparison of failure modes in pre and post 1978 manufactured power station transformers

7.5. STATISTICAL ANALYSIS

Table 19 to Table 24 give the age groups of the hazard function periods for transmission transformers, obtained from the hazard functions in Figure 24 to Figure 35 when the data is analysed as CD and MCD using the RF and HP techniques. The tables also indicate the major contributors of failure in each of the periods in terms of failure locations, causes and modes. The failure causes and modes in Table 19 and Table 21 do not necessarily relate to the failure location identified as the major contributor in a particular hazard function period.

As discussed in chapters 4 and 6, the hazard function gives the instantaneous failure rate (IFR) with age. General observations from the hazard functions in Figure 24 and Figure 25 include the following:

- The data types and plotting techniques did not result in the same hazard functions per manufacturing period.
- With CD analysis there were some similarities between the plotting methods.
- The most significant differences between the plotting techniques were observed with MCD analysis.
- Analysis as MCD indicated lower IFRs than CD.

7.5.1. Complete Failures

The hazard functions for the combined group of transmission transformers in complete failure analysed as CD and MCD are given in Figure 24 and Figure 25, and information obtained from them summarised in Table 19.

Due the data limitation, 60% of the transmission transformers in complete failure could not be classified into failure locations and causes, and nearly 70% could not be classified into failure modes. Further, about 75% of the pre 1978 transformer failures were unclassified in terms of failure locations, failure causes and failure modes. The significance of the major contributors in the hazard function periods of pre 1978 manufactured units could therefore not be assessed, and a comparison regarding reliability according to manufacturing period could not be made.

When using the HP method as both data types, and using CD with the RF method, the onset of increasing IFRs after the constant or lower IFR period appeared to occur earlier in post 1978 manufactured units, than in pre 1978 manufactured transformers.

Apart from the peaking periods, there was agreement with the hazard function interpretation of transformer data for both manufacturing periods, when analysed as CD using both plotting methods. Peaking periods indicated by the RF method did not result in inherent deficiencies as expected, but were predominantly tap changer related and due to inherited deficiencies.

When analysed as MCD using the RF method, only the sharply increasing period agreed with the expected interpretation. The RF method also featured as decreasing period which featured inherited deficiencies and abnormal deterioration; the peaking period also indicated inherited deficiencies. The two periods (constant and increasing) indicated by the HP method agreed with the interpretation.

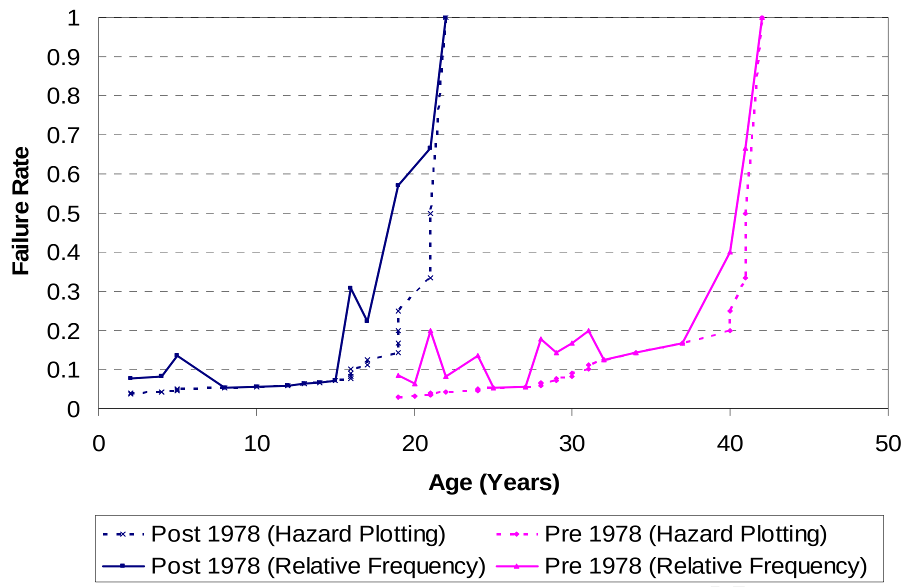


Figure 24: Hazard function of transmission transformers in complete failures according to manufacturing period using CD analysis

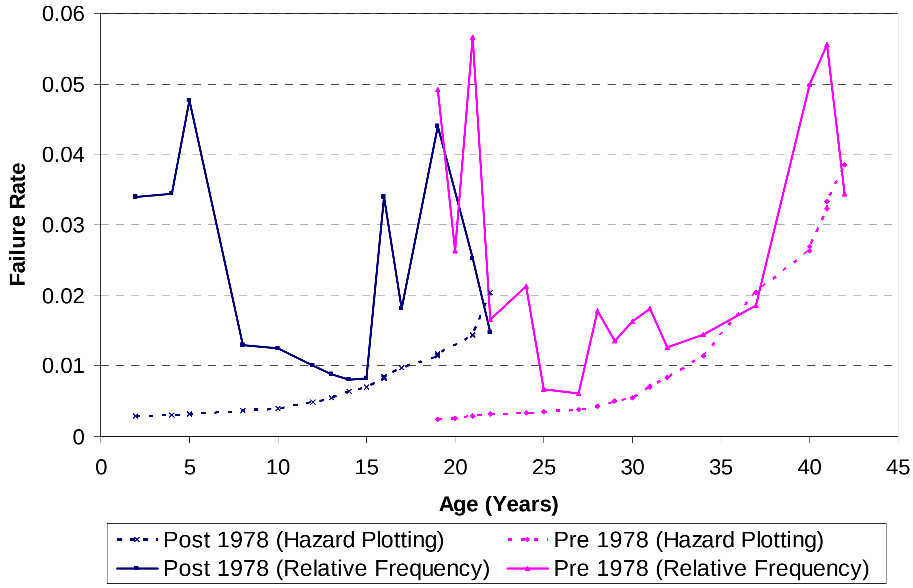


Figure 25: Hazard function of transmission transformers in complete failures according to manufacturing period using MCD analysis

Table 19: Summary of information obtained from the hazard function periods of transmission transformers in complete failures in Figure 24 and Figure 25, with major contributors of failure locations, causes and modes

Data Type	Manufacturing Period	Plotting Method	Constant Period	Increasing Period	Sharply Increasing Period	Decreasing Period	Peaking Period
Complete Data	Post 1978	RF	**8 – 15 yrs** WI, TC ID2, AD D		**> 15 yrs** WI SE, AD D, M		**2 – 5 yrs** TC ID2 E
		HP	**2 – 15 yrs** TC ID2 D, E		**> 15 yrs** WI SE, AD D, M		
Multiply Censored Data	Post 1978	RF			**> 15 yrs** WI SE, AD D, M	**8 – 15 yrs** WI, TC ID2, AD D	**2 – 5 yrs** TC ID2 E, M
		HP	**2 – 12 yrs** TC ID2 E	**> 12 yrs** WI SE, AD D, M			

Failure Locations: B: Bushings, WI: Windings & Insulation, TC: Tap Changer, NS: No Significance

Failure Causes: ID1: Inherent Deficiencies, ID2: Inherited Deficiencies, SE: System Events, AD: Abnormal Deterioration

Failure Modes: D: Dielectric, M: Mechanical, E: Electrical

7.5.2. Complete Failures: Windings & Insulation

The hazard functions of transformers in winding related complete failures, analysed as CD and MCD, are given in Figure 26 and Figure 27, and information obtained from them summarised in Table 20.

When using the HP method as both data types, the onset of increasing IFR's after the constant or lower IFR period appeared to occur earlier in post 1978 manufactured units, than in pre 1978 manufactured transformers.

When analysed as CD, the hazard function periods agreed with the theory in both plotting techniques in pre and post 1978 manufactured transformers.

Analysis of the post 1978 sample as MCD with the HP method agreed with the interpretation, in the increasing and sharply increasing periods. With the RF method, only the sharply increasing periods agreed; peaking periods featured system events, and the decreasing period system events and abnormal deterioration.

The increasing period of the pre 1978 sample using the HP method agreed with the interpretation. The decreasing period indicated by the RF method had inherited deficiencies and system events as major contributors.

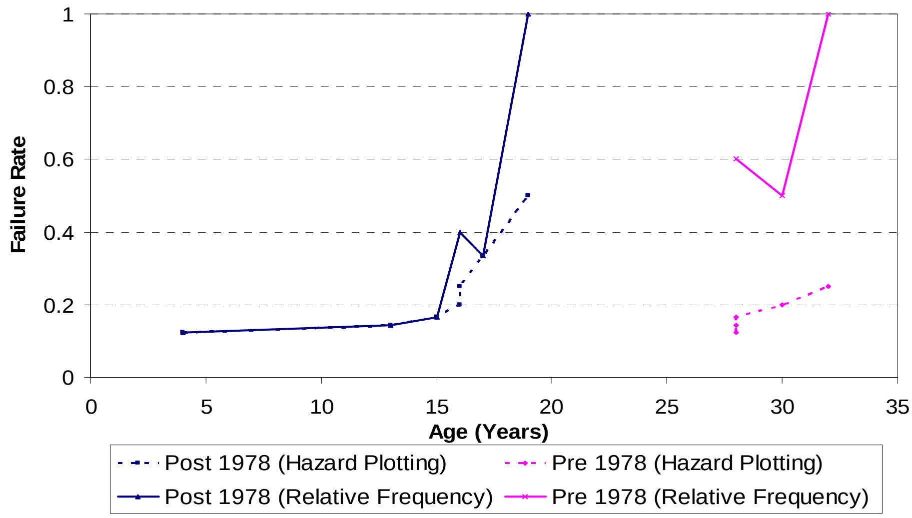


Figure 26: Hazard function of transmission transformers in complete failures in winding & insulation related failures using CD analysis

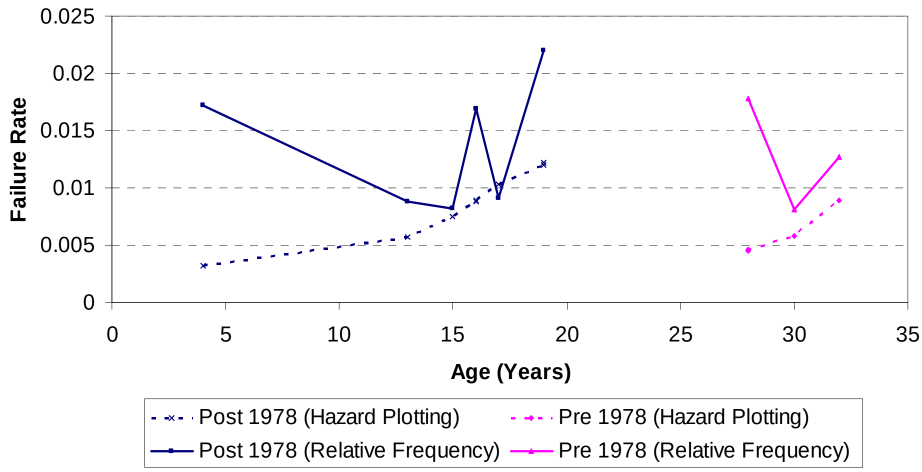


Figure 27: Hazard function determined from MCD analysis for transformers in winding & insulation related failures

Table 20: Summary of information obtained from the hazard functions of transmission transformers in winding and insulation related complete failures in Figure 26 and Figure 27, with major contributors of failure causes and failure modes

Data Type	**Manufacturing Period**	**Plotting Method**	**Constant Period**	**Increasing Period**	**Sharply Increasing Period**	**Decreasing Period**	**Peaking Period**
Complete Data	Post 1978	RF	**4 – 15 yrs** SE, AD D, M		**> 15 yrs** SE, AD M, D		
Complete Data	Post 1978	HP	**4 – 15 yrs** SE, AD D, M		**> 15 yrs** SE, AD M		
Complete Data	Pre 1978	RF			**> 28 yrs** ID2, SE D		
Complete Data	Pre 1978	HP		**> 28 yrs** ID2, SE D			
Multiply Censored Data	Post 1978	RF			**> 15 yrs** SE, AD M, D	**4 – 15 yrs** SE, AD D, M	**4yrs** SE M
Multiply Censored Data	Post 1978	HP		**4 – 15 yrs** SE, AD D, M	**> 15 yrs** SE, AD M, D		
Multiply Censored Data	Pre 1978	RF				**> 28 yrs** ID2, SE D	
Multiply Censored Data	Pre 1978	HP		**> 28 yrs** ID2, SE D			

Failure Causes: SE: System Events, AD: Abnormal Deterioration, ID2: Inherited Deficiencies

Failure Modes: D: Dielectric, M: Mechanical

7.5.3. Failures with Repairs

The hazard functions of transmission transformers in failures with repairs, and analysed as CD and MCD, are given in Figure 28 and Figure 29, and information obtained from them summarised in Table 21.

When analysed as both data types using the HP method, the onset of increasing IFRs occurred earlier in the post 1978 sample.

When analysed as CD using both plotting techniques, the group of post 1978 manufactured transformers agreed with the expected interpretation in the constant periods. However, the increasing and sharply increasing periods featured inherited deficiencies which were expected in the constant/low IFR periods, and inherent deficiencies which were expected in the peaking periods.

Pre 1978 manufactured units only agreed with the interpretation in the constant periods. The increasing periods indicated inherited deficiencies as a major contributor.

When analysing the post 1978 manufactured units as MCD using the RF method, only the sharply increasing period and the earlier peaking period (9 years) agreed with the expected interpretation. Later life peaking periods had inherited deficiencies and environmental factors as major contributors. With the HP method, the constant period and sharply increasing period agreed with the interpretation. The constant period also included inherent deficiencies and abnormal deterioration. The increasing period resulted in inherited deficiencies and failures due to environmental factors.

In pre 1978 manufactured units using both plotting methods, the constant periods agreed with the interpretation. The increasing periods featured inherited deficiencies, and the peaking period identified by the RF method had system events as the major contributor. The decreasing period indicated by the RF method had no significance.

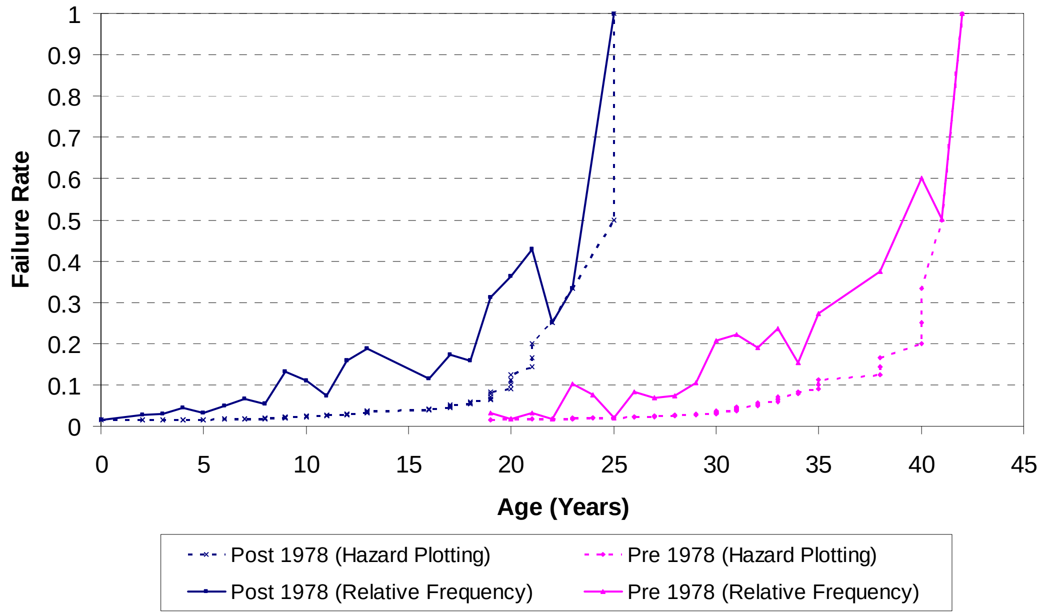


Figure 28: Hazard function of transmission transformers in failures with repair, determined from CD analysis

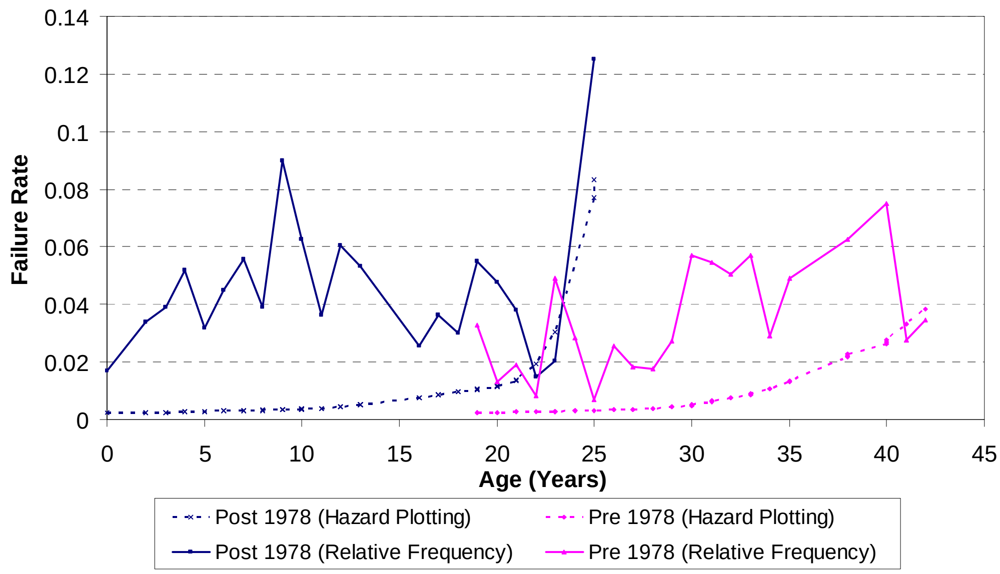


Figure 29: Hazard function of transmission transformers in failures with repair, determined from MCD analysis

Table 21: Summary of information obtained from hazard functions for transmission transformers in failures with repairs in Figure 28 and Figure 29, with major contributors of failure locations, causes and modes

Data Type	**Manufacturing Period**	**Plotting Technique**	**Constant/ Low Period**	**Increasing Period**	**Decreasing Period**	**Sharply Increasing Period**	**Peaking Period**
Complete Data	Post 1978	RF	**0 – 8 yrs** TC, CS ID2 D, M	**9 – 18 yrs** B, TC ID2, ID1, AD D, M		**> 18 yrs** TC, B, P ID2, AD D, M	**19 – 21 yrs** P, B, TC ID2, E D, M
		HP	**0 – 10 yrs** B, TC, CS ID2, ID1 D, M	**11 – 19 yrs** B, TC ID2, AD D, M		**> 19 yrs** B, P, TC E, ID2, AD D, M	
	Pre 1978	RF	**19 – 22 yrs** NS NS NS			**> 29 yrs** B, TC ID2 M	
			23 – 29 yrs B, TC ID2 M				
		HP	**19 – 30 yrs** B, TC ID2 M	**31 – 38 yrs** B, TC ID2 M		**> 38 yrs** B NS NS	
Multiply Censored Data	Post 1978	RF		**0 – 9 yrs** TC, B, CS ID2 D, M	**10 – 23 yrs** B, TC ID2 D, M	**> 23 yrs** B AD D	**9 yrs** B ID1 D
							19 – 21 yrs P, B, TC ID2, E D, M
		HP	**0 – 13 yrs** B, TC ID2, ID1, AD D, M	**14 – 21 yrs** TC, B, P ID2, E M, D		**> 21 yrs** B, TC AD M	
	Pre 1978	RF	**24 – 29 yrs** B, TC ID2 M, D	**> 29 yrs** B, TC ID2 D, M	**19 – 22 yrs** NS NS NS		**23 yrs** TC SE M
		HP	**19 – 30 yrs** B, TC ID2 M	**> 30 yrs** B, TC ID2 D, M			

Failure Locations: B: Bushings, TC: Tap Changer, CS: Cooling System, NS: No Significance
Failure Causes: ID1: Inherent Deficiencies, ID2: Inherited Deficiencies, AD: Abnormal Deterioration, SE: System Events, E: Environmental, NS: No Significance
Failure Modes: D: Dielectric, M: Mechanical, NS: No Significance

7.5.4. Failures with Repair: Windings & Insulation

The hazard functions of transmission transformers in winding and insulation related repair failures, and analysed as CD and MCD, are given in Figure 30 and Figure 31, and information obtained from them summarised in Table 22

When analysed as CD using both data plotting techniques, and MCD using the HP method, the onset of increasing IFRs occurred earlier in the post 1978 sample.

The hazard function periods resulting from both plotting techniques when analysed as CD agreed with the expected interpretation in pre and post 1978 manufactured transformers. However, inherited deficiencies did also feature as a major contributor in the increasing periods.

The hazard function of the sample of post 1978 manufactured units using the HP method agreed with the interpretation in increasing and sharply increasing periods. Increasing periods also featured inherited deficiencies. The increasing period indicated by the RF method also agreed with the interpretation; the decreasing period featured inherited deficiencies and the peaking period at 3 years had no significance.

In the pre 1978 sample, the increasing periods of both plotting methods had no significance. The constant period indicated by the HP method no agreement with the hazard function interpretation, and the decreasing period indicated system events as the major contributor.

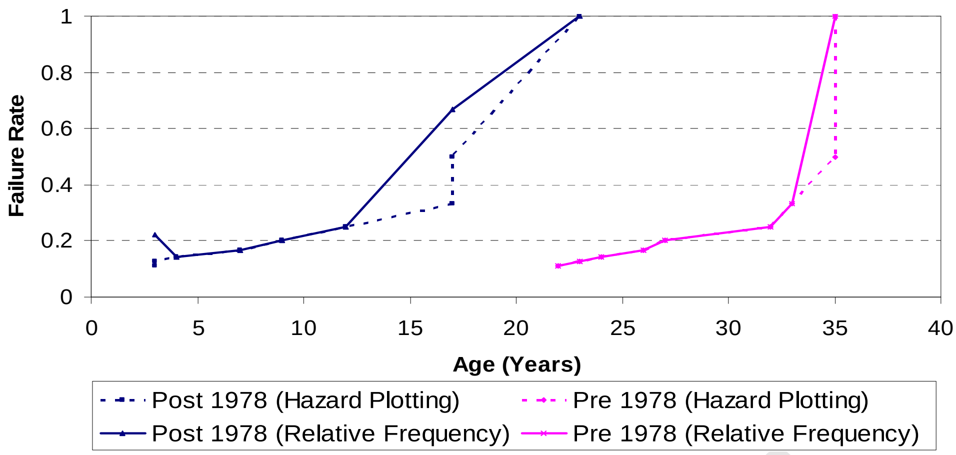


Figure 30: Hazard function determined from CD analysis for transmission transformers in winding related failures with repair

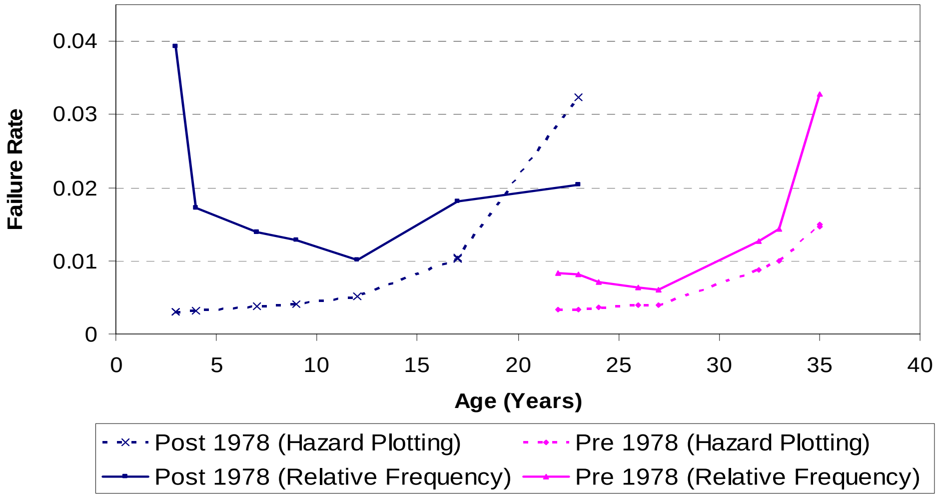


Figure 31: Hazard function determined from MCD analysis for transformers in winding related failures with repair

Table 22: Summary of information obtained from the hazard functions for transmission transformers in winding related failures with repair in Figure 30 and Figure 31, with major contributors of failure causes and modes

Data Type	**Manufacturing Period**	**Plotting Technique**	**Constant/ Low Period**	**Increasing Period**	**Decreasing Period**	**Sharply Increasing Period**	**Peaking Period**
Complete Data	Post 1978	RF		**4 – 12 yrs** ID2, AD NS		**> 12 yrs** SE, AD M	**3 yrs** NS NS
		HP		**3 – 17 yrs** ID2, AD, SE D, M		**> 17 yrs** NS NS	
	Pre 1978	RF		**22 – 32 yrs** SE M		**> 32 yrs** NS NS	
		HP		**22 – 32 yrs** SE M		**> 32 yrs** NS NS	
Multiply Censored Data	Post 1978	RF		**> 12 yrs** SE, AD M	**4 – 12 yrs** ID2, AD NS		**3 yrs** NS NS
		HP		**3 – 12 yrs** ID2, AD, SE D, M		**> 12 yrs** SE, AD M	
	Pre 1978	RF		**> 27 yrs** NS NS	**22 – 27 yrs** SE M		
		HP	**22 – 27 yrs** SE M	**> 27 yrs** NS NS			

Failure Causes: ID2: Inherited Deficiencies, AD: Abnormal Deterioration, SE: System Events, NS: No Significance

Failure Modes: D: Dielectric, M: Mechanical, NS: No Significance

7.5.5. Failures with Repairs: Bushings

The hazard functions of transmission transformers in bushing related failures with repairs, and analysed as CD and MCD, are given in Figure 32 and Figure 33, and information obtained from them summarised in Table 23.

When analysed as CD using both data plotting techniques, and MCD using the HP method, the onset of increasing IFRs occurred earlier in the post 1978 sample.

When post 1978 manufactured transformers were analysed as CD using both plotting techniques, there was agreement with the expected interpretation of the hazard function periods, but inherited deficiencies also featured. There was no agreement with pre 1978 manufactured transformers.

When analysed as MCD using the RF method, the peaking, increasing and sharply increasing periods of the post 1978 sample had no significance. The decreasing period featured abnormal deterioration. When using the HP method, the constant and increasing periods did not agree with the expected interpretation. The constant period indicated abnormal deterioration and inherent deficiencies as major contributors, while the increasing period featured failures due to environmental factors.

In the pre 1978 sample, the constant period agreed with the interpretation in both plotting methods. Increasing periods in both plotting methods and the peaking period indicated by the RF method were due to inherited deficiencies.

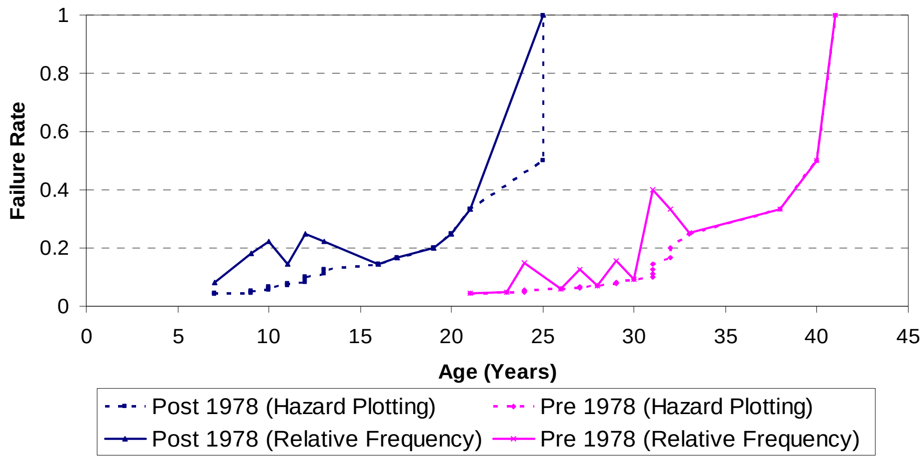


Figure 32: Hazard function determined from CD analysis for transformers in bushing related failures with repair

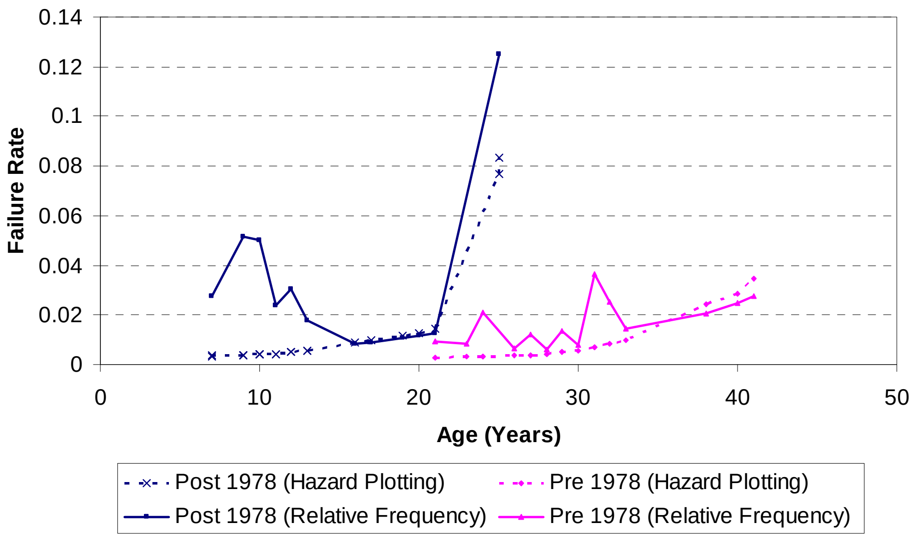


Figure 33: Hazard function determined from MCD analysis for transformers in bushing related failures with repair

Table 23: Summary of information obtained from the hazard functions for transmission transformers in bushing related failures with repair in Figure 32 and Figure 33, with failure causes and modes

Data Type	Manufacturing Period	Plotting Technique	Constant/ Low Period	Increasing Period	Decreasing Period	Sharply Increasing Period	Peaking Period
Complete Data	Post 1978	RF		**7 – 19 yrs** ID1, AD, ID2 M, D		**> 19 yrs** NS NS	**10 yrs** NS NS
Complete Data	Post 1978	RF					**12 yrs** AD NS
Complete Data	Post 1978	HP		**7 – 19 yrs** ID1, AD, ID2 M, D		**> 19 yrs** NS NS	
Complete Data	Pre 1978	RF		**21 – 30 yrs** ID2 D, M		**> 30 yrs** ID2 M	**31 yrs** ID2 NS
Complete Data	Pre 1978	HP		**21 – 30 yrs** ID2 D, M		**> 30 yrs** ID2 M	
Multiply Censored Data	Post 1978	RF		**17 – 21 yrs** NS M	**11 – 16 yrs** AD D, M	**> 21 yrs** NS NS	**9 yrs** NS NS
Multiply Censored Data	Post 1978	RF					**10 yrs** NS NS
Multiply Censored Data	Post 1978	HP	**7 – 13 yrs** AD, ID1 D, M	**14 – 21 yrs** E M		**> 21 yrs** NS NS	
Multiply Censored Data	Pre 1978	RF	**21 – 30 yrs** ID2 D, M	**> 30 yrs** ID2 M			**31 yrs** ID2 NS
Multiply Censored Data	Pre 1978	HP	**21 – 30 yrs** ID2 D, M	**> 30 yrs** ID2 M			

Failure Causes: ID1: Inherent Deficiencies, ID2: Inherited Deficiencies, AD: Abnormal Deterioration, E: Environmental, NS: No Significance

Failure Locations: D: Dielectric, M: Mechanical, NS: No Significance

7.5.6. Failures with Repairs: Tap Changers

The hazard functions of transmission transformers in tap changer related failures with repairs, and analysed as CD and MCD are given in Figure 34 and Figure 35, and information obtained from them summarised in Table 24.

When analysed as CD using both data plotting techniques, and MCD using the HP method, the onset of increasing IFRs occurred earlier in the post 1978 sample.

Only the constant and sharply increasing periods agreed with the expected interpretation of the hazard function when post 1978 manufactured transformers were analysed as CD using both plotting methods. Inherent and inherited deficiencies occurred in the increasing periods of pre and post 1978 manufactured transformers, which were expected in the peaking and constant/low periods, respectively. The peaking periods of pre and post 1978 manufactured transformers featured inherent deficiencies, and were in agreement with the expected interpretation. The peaking periods also included inherited deficiencies and environmental factors.

When analysed as MCD using both plotting techniques, the constant periods agreed with the expected interpretation. The early life peaking period indicated by the RF method also agreed with the interpretation. The increasing period of the RF method had inherited deficiencies, and the HP method featured inherent deficiencies. The decreasing period of the RF method also featured inherent deficiencies. The sharply increasing period indicated by the HP method had inherited deficiencies as the major contributor.

For the pre 1978 sample, the decreasing and peaking periods indicated by the RF method, and the constant period indicated by the HP method, had no significance. The increasing and sharply increasing periods of pre 1978 sample showed no agreement with the expected interpretation. The increasing and sharply increasing periods featured inherited and inherent deficiencies as major contributors.

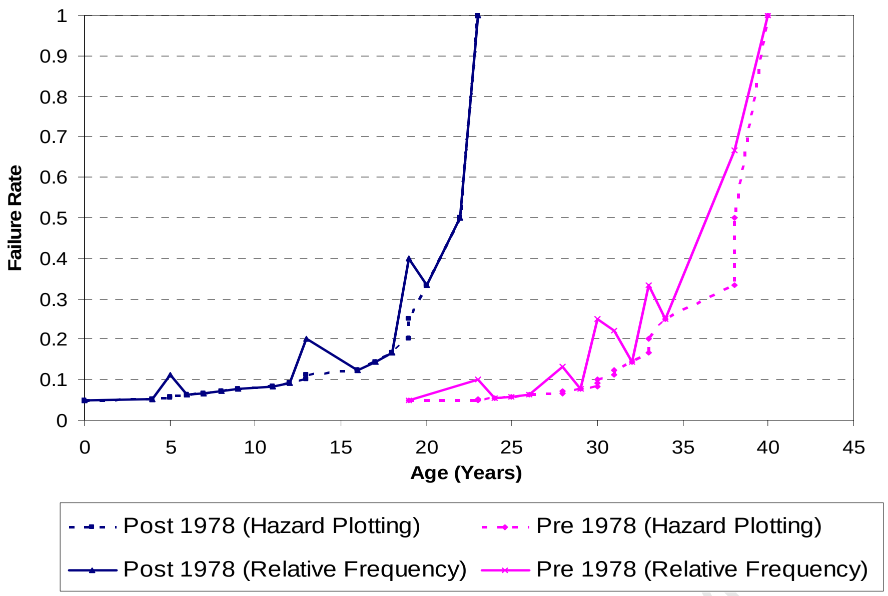


Figure 34: Hazard function determined from CD analysis for transmission transformers in tap changer related failures with repair

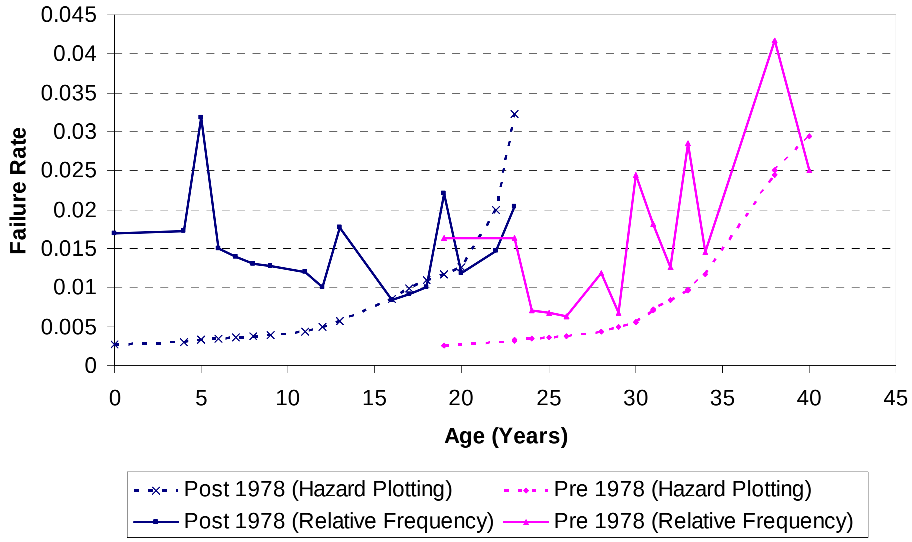


Figure 35: Hazard function determined from MCD analysis for transformers in tap changer related failures with repair

Table 24: Summary of information obtained from the hazard functions for transmission transformers in tap changer related failures with repair in Figure 34 and Figure 35, with major contributors of failure causes and modes

Data Type	Manufacturing Period	Plotting Technique	Constant/ Low Period	Increasing Period	Decreasing Period	Sharply Increasing Period	Peaking Period
Complete Data	Post 1978	RF	**0 – 4 yrs** ID2 E	**6 – 18 yrs** ID1, ID2 D		**> 18 yrs** ID2, AD M	**5 yrs** ID2, ID1 D, PC
							13 yrs E D
							19 yrs ID2 M
		HP	**0 – 5 yrs** ID2 NS	**6 – 18 yrs** ID1, ID2 D		**> 18 yrs** ID2, AD M	
	Pre 1978	RF	**24 – 26 yrs** NS NS			**> 28 yrs** ID2, ID1 M	**23 yrs** NS M
							28 yrs ID2 M
							30 – 31 yrs ID1 M
							33 yrs ID1 NS
		HP	**19 – 26 yrs** NS M	**27 – 30 yrs** ID2, ID1 M		**> 30 yrs** ID2 M	
Multiply Censored Data	Post 1978	RF	**0 – 4 yrs** ID2 E	**16 – 23 yrs** ID2 M	**6 – 12 yrs** ID1 D		**5, 13, 19 yrs** Refer to CD Analysis.
		HP	**0 – 5 yrs** ID2 NS	**6 – 12 yrs** ID1 D		**> 12 yrs** ID2 D, M	
	Pre 1978	RF			**24 – 26 yrs** NS NS	**> 26 yrs** ID2, ID1 M	**19 – 23 yrs** NS M
		HP	**19 – 23 yrs** NS M	**24 – 30 yrs** ID1, ID2 M		**> 30 yrs** ID2 M	

Failure Causes: ID1: Inherent Deficiencies, ID2: Inherited Deficiencies, AD: Abnormal Deterioration, E: Environmental, NS: No Significance

Failure Modes: D: Dielectric, M: Mechanical, PC: Physical Chemistry, E: Electrical, NS: No Significance

7.6. SUMMARY

This chapter addressed the following research question/aspects:

- What trends can be observed in the reliability/failure of transformers according to manufacturing periods?
- Assessing the agreement of the hazard function periods of different groups of transformers with the expected hazard function interpretation for transformer data, when the data was analysed as CD and MCD. If there was agreement, identify trends in reliability/failure according to manufacturing period.

The extent to which these questions have been answered is summarised in the results below.

7.6.1. AAFR According to Manufacturing Period

7.6.1.1. Comparison with Industry Benchmark

The AAFR of pre and post 1978 manufacture units with tap changers is virtually the same, and almost 1% higher than the industry benchmark.

7.6.1.2. Significance with Highest System Voltage

The AAFR increased with increasing system voltage in both manufacturing periods.

Post 1978 manufactured units in both transformer applications had higher AAFR's than pre 1978 manufactured units in the 100kV to 300kV range, the most significant difference being in the power station transformers (GSUs).

7.6.1.3. Significance with Transformer Application

AAFR of post 1978 manufactured power station transformers (GSUs) were higher than pre 1978 units; pre 1978 substation and autotransformers were higher than post 1978 units.

7.6.1.4. Significance with Age at Failure

The AAFR was relatively constant with increasing age groups, in both manufacturing periods.

Post 1978 manufactured transformer AAFR were higher than pre 1978 units in the first 5 years in the 100kV to 700kV range; and in mid life from 10 to 20 years in the 300kV to 700kV range, and the combined group of post 1978 transformers.

7.6.2. Failures Classification According to Manufacturing Period

In most cases the failure classification by manufacturing periods remained unchanged with transformer application, in particular:

- Substation and autotransformers: Tap changer and winding related failures as failure locations, inherited and inherent deficiencies as failure causes, dielectric and mechanical mode failures as failure modes.
- Power Station Transformers: Winding and terminal as failure locations, inherent deficiencies as failure causes, thermal and mechanical as failure modes.
- Failures related to the magnetic circuit (core) were a minor contributor in both transformer applications, irrespective of manufacturing period.

The only cases where there was a difference in the major contributors was the fact that terminal (bushings) were a major contributor in post 1978, and not in pre 1978 manufactured units; other accessories were a major contributor in pre 1978 units, but not in post 1978 units.

The most significant observations regarding the failure locations are discussed below.

7.6.2.1. Terminal Related Failures

Terminals were predominantly bushing related in the group of post 1978 manufactured units. The contribution in pre 1978 manufactured units was lower than in post 1978 manufactured units.

Bushing related failures in post 1978 manufactured transmission transformers were mainly due to abnormal deterioration, inherent (inadequate design or manufacturing) and inherited deficiencies (improper maintenance and improper factory assembly). The distribution transformers in bushing failures occurred in the three coastal regions on the distribution network.

Inherent deficiencies such as inadequate design and manufacturing related problems, coupled with abnormal deterioration, in transmission units featured in the first 15 years in post 1978 manufactured units. Where failure modes could be identified, they were of the mechanical type.

Inherent deficiencies (inadequate design) were a major contributor of terminal (winding connections) related failures in GSUs. These failures occurred in units from 14 years, were predominantly thermal mode failures and from one manufacturer.

7.6.2.2. Tap Changer Related Failures

Tap changers were among the major contributors of failure in substation and autotransformers, irrespective of manufacturing period. Failures in post 1978 manufactured transmission transformers were mostly due to inherited (improper maintenance, repair and factory assembly) and inherent deficiencies (design and manufacturing), and had their onset from 4 to 5 years.

In power station transformers, tap changers were among the minor contributors of failure.

7.6.2.3. Winding Related Failures

Winding related failures featured as a major contributor, irrespective of transformer application and manufacturing period.

In post 1978 manufactured transmission transformers, failures were due to system events, abnormal deterioration and inherited deficiencies. Failures due to system events occurred predominantly in the North Eastern region on the transmission network.

In the sample of distribution transformers, one manufacturer contributed to the majority of the failures in the first 10 years. The distribution sample also indicated a regional significance, where failures above 10 years occurred predominantly in the Eastern region, a coastal region with high humidity.

Failures in post 1978 manufactured power station transformers were mostly due to system events, inherent deficiencies (inadequate design or manufacture) and abnormal deterioration.

7.6.2.4. Core Related Failures

Failures originating in the core were a minor contributor in both manufacturing periods of substation and autotransformers and in pre 1978 manufactured power station transformers.

7.6.2.5. Other Accessories

Other accessories were a major contributor in pre 1978 manufactured substation and autotransformers, but not in the post 1978 sample. In the post 1978 sample, other accessories contributed to failures that developed in the cooling system, due to maintenance and repair related inherited deficiencies. The failure mode was predominantly of the mechanical type.

7.6.3. Statistical Analysis

7.6.3.1. Data Types and Plotting Techniques

The data types and plotting techniques did not result in the same hazard functions per manufacturing period. With CD analysis, there were some similarities between the plotting methods. The most significant differences between the plotting techniques were observed with MCD analysis.

7.6.3.2. Agreement with Hazard Function Interpretation

- Data Analysed as CD

Apart from the peaking periods, the transmission data showed agreement with the expected hazard function interpretation, in complete failures of units from both manufacturing periods.

There was no consistency in the assessment of repair failures. Post 1978 manufactured transformers showed more agreement with the expected interpretation. Inherited deficiencies which were expected in the constant or low periods, and inherent deficiencies which were expected in the peaking periods, featured predominantly in the increasing and sharply increasing periods. In the evaluation of tap changer related failures, the peaking periods featured inherent deficiencies, along with inherited deficiencies and environmental factors.

- Data Analysed as MCD

When complete failures were analysed as MCD using the HP method, all the identified periods agreed with the expected interpretation. With the failures with repairs, in some cases only certain periods agreed with the expected interpretation which varied with samples taken (only repair failures, by failure location), and in other cases there was no agreement.

When analysed as MCD using the RF method, only certain periods agreed with the expected interpretation and varied with the samples taken (complete failures, repair failures and failures by location).

Where peaking periods occurred in both pre and post 1978 manufactured transformers, the major contributors were inherited deficiencies, system events and inherent deficiencies. Inherent deficiencies featured as an early life peak only in the sample of post 1978 tap changer related failures with repair.

Where decreasing periods occurred, the major contributors were inherited deficiencies, abnormal deterioration, system events and inherent deficiencies.

7.6.3.3. Trends in Reliability According to Manufacturing Period

In the sample of transmission transformers in complete failures and failures with repair, the onset of increasing IFRs after the constant period occurred earlier in post 1978 manufactured unit when the sample was analysed as CD and MCD using the HP method and as CD using the RF method.

7.6.4. Next Steps

The most significant results of the data analysis was presented in terms of the AAFR, failures classification (failure locations, causes and modes), and the application of statistical analysis.

The failures classification of the different groups of transformers showed some regional significance. In the next chapter, regional characteristics of the distribution and transmission network will be discussed, along with interpretation and discussion of the results.

CHAPTER 8: DISCUSSION OF RESULTS

8.1. AAFR ACCORDING TO MANUFACTURING PERIOD

Although the AAFR according to manufacturing period indicated no change in reliability, the breakdown into transformer application, voltage groups, and age groups suggested that post 1978 manufactured units experienced poorer reliability. This occurred in particular, in the higher voltage ranges of both transformer applications, and in early and mid life of the higher voltage ranges above from 100kV.

The voltage levels of the samples of pre and post 1978 manufactured transformers were equivalent. Higher voltage transformers are usually larger units and require more material (conductors, oil and paper insulation) and design engineers are required to ensure that transformers are within the allowable transportation limits.

In the pre 1978 period, transformer design engineers were required to ensure a tolerable design using numerical design methods. With computer aided design techniques and increasing competition in the global markets in the post 1978 period, internal clearances could be further reduced, resulting in lower oil volumes and a reduction in insulation material [Kulkarni, 2004]. The margin between withstand levels and operating stress levels has thus been decreasing, which could be a reason for the higher failure rate observed in the post 1978 manufactured transformers in the higher voltage ranges.

Other possible factors that could have resulted in a different inference of reliability with manufacturing periods:

- Unknown failures that were not included in the South African database or those that were not included as part of the statistics in Bossi [1983].
- Comparison of shorter or different manufacturing periods.
- Comparison of the AAFR with manufacturing period by transformer manufacturer.
- Availability of South Africa's pre 1978 manufactured transformer failure data for true comparison with post 1978 failures.
- The results from other studies, not covered by the literature survey, could have suggested a different inference of reliability.

8.2. REGIONAL CHARACTERISTICS

The failures classification indicated some regional significance with the spread of failures. Before discussing the results, the characteristics of the regions on the distribution and transmission networks in South Africa will be discussed.

The distribution network consists of 6 regions (Figure 36). Although the transmission network has 7 regions, many boundaries are similar to those of the distribution network.

Regions A, B and C are predominantly coastal regions with some areas classified as inland. Regions D, E and F are classified as inland.

The distribution transformer failures occurred in three regions: A, B and C. Transmission transformers failed in all the regions. The coastal belts of these three regions are characterised by high humidity (Figure 37), the highest being in the region C, and heavy saline pollution.

The humidity values of the Western Cape, Eastern Cape and Kwa-Zulu Natal given in (Figure 37) represent regions A, B and C, respectively. The humidity values were obtained from the South African weather service and were based on historical data over the period 2005 to 2009.

Region A has a Mediterranean climate and is exposed to winter rainfall, whereas region C has a sub-tropic climate with summer rainfall (Figure 38) and greater lightning intensity (Figure 39). Region B has no seasonal variation in rainfall and gets rain all year.

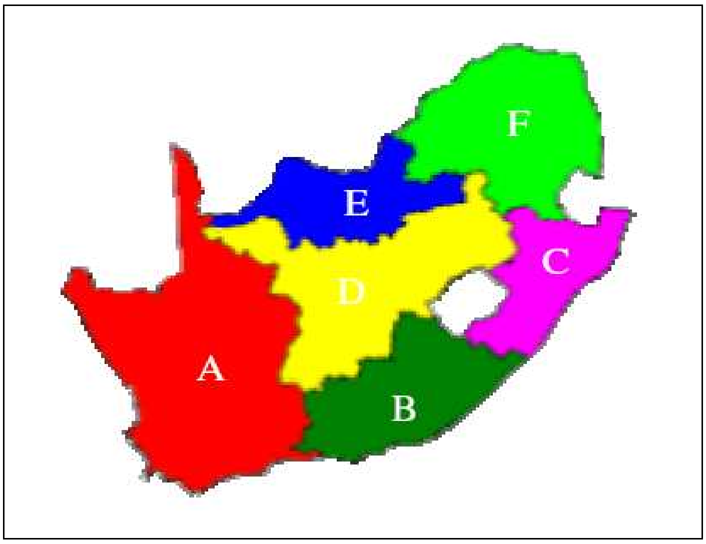


Figure 36: Regions of the South African distribution network [Eskom Dx, URL 1]

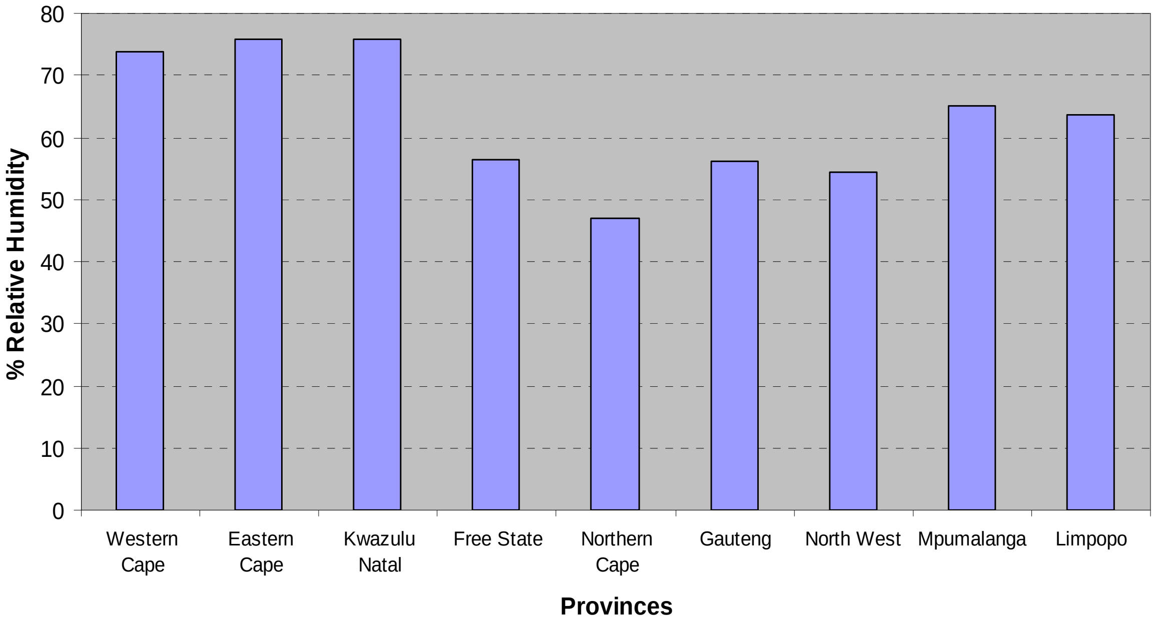


Figure 37: Average annual relative humidity in South Africa during the period 2005 to 2009

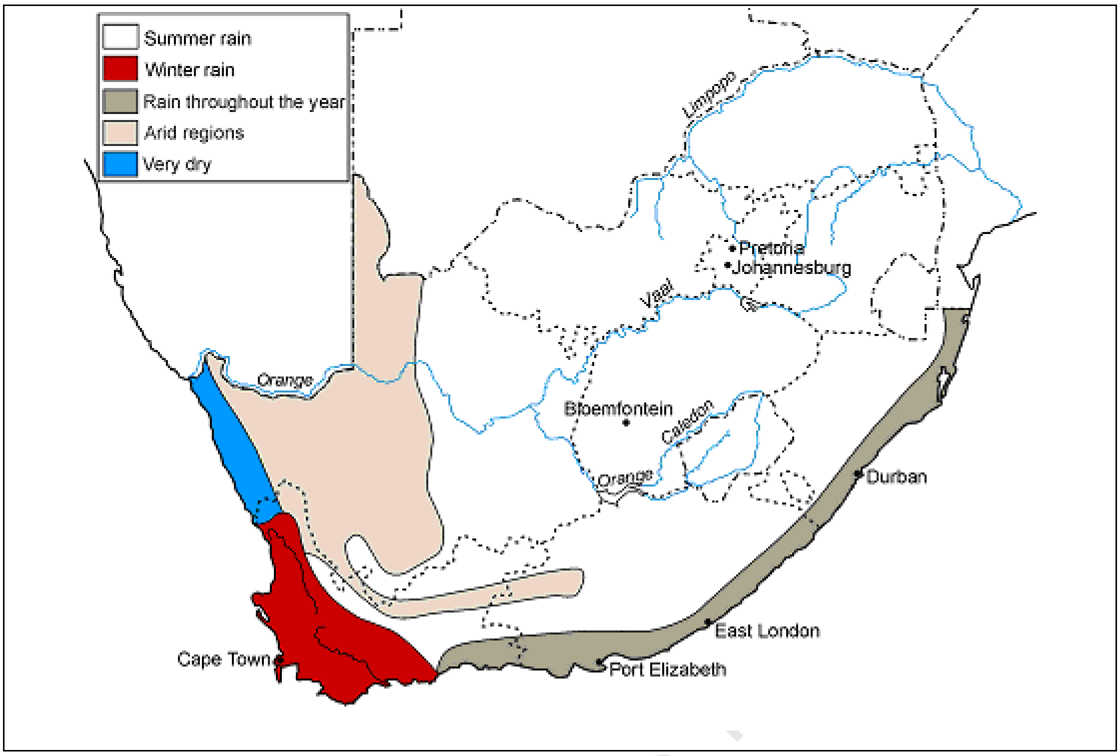


Figure 38: Seasonal rainfall in South Africa [CNX, URL 1]

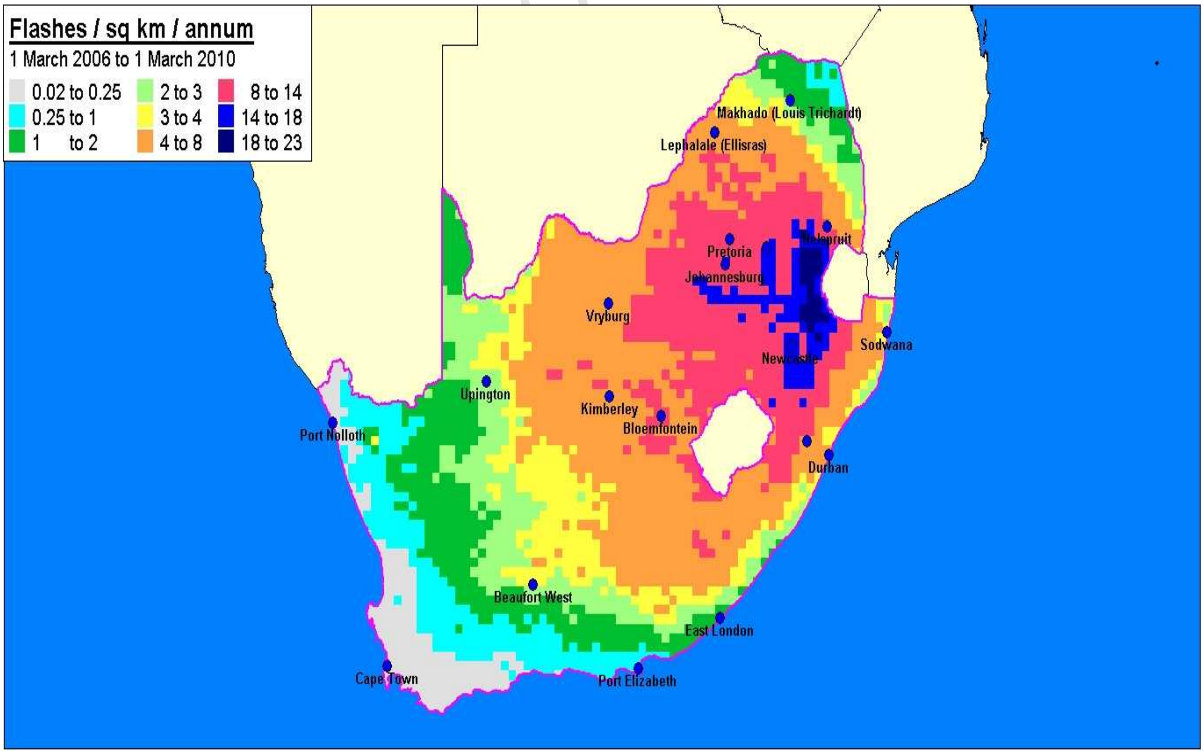


Figure 39: Lightning intensity in South Africa [Eskom, 2010]

8.3. FAILURES CLASSIFICATION ACCORDING TO MANUFACTURING PERIOD

The fact that the majority of the major contributors to failure have remained unchanged with manufacturing period could suggest that the developments in design, manufacture and technology had no impact on transformer reliability.

The only case where there was a difference in the major contributors were the terminals (bushings), which were a major contributor in post 1978, but not in pre 1978 manufactured units; other accessories were major contributors in pre 1978 units, but not in post 1978 units.

Since the identified failure causes and modes, as well as the developments in design, manufacture and technology, all refer to parts (locations) in the transformer, discussions of the results were done by failure location for tap changers, terminals (bushing and winding connections), windings, the core and other accessories.

8.3.1. Terminal (Bushing) Related Failures

According to the literature, earlier bushings were of the resin bonded paper type and from the 1940's, they were of the oil impregnated paper type, with an outer porcelain insulator. It can therefore be assumed that the pre 1978 manufactured bushings were of the abovementioned two types. According to the data, the group of post 1978 units were all fitted with the oil impregnated paper type bushings with the porcelain insulator.

Bushing related failures in post 1978 manufactured transmission transformers were mainly due to abnormal deterioration, inherent (inadequate design or manufacturing) and inherited deficiencies (improper maintenance and improper factory assembly). The distribution transformers in bushing failures occurred in the three coastal regions on the distribution network. Regional characteristics include pollution (saline and industrial), strong winter rainfall and strong winds, high humidity and lightning intensity.

The failures due to maintenance related inherited deficiencies and abnormal deterioration in post 1978 transmission transformers, and the regional significance observed in the distribution transformers can therefore all be traced back to the bushing technology that was used, in particular the porcelain insulator. The literature survey in chapter 3 also identified the technology used at the time as being the main factor in the unreliability of bushings.

Terminals (bushings) were a major contributor to failure in post 1978 manufactured transformers, but not in pre 1978 manufactured transformers. In addition to this, the contribution of terminal related failures was also less in pre 1978 manufactured transformers than in post 1978 manufactured units. Since the porcelain insulator was used in both manufacturing periods, the more pronounced contribution in post 1978 manufactured units could be attributed to increased industrial pollution because of increasing industries (mining, fossil fuelled power generation, industrial factories etc.). More pollution and the associated impact on the bushing insulator (discussed in chapter 3), could have made the post 1978 bushings more susceptible to failure and ultimately of poorer reliability.

As discussed in chapter 3, to eliminate the aforementioned problems, there have been changes in the specification of bushings in Eskom which included changes to the bushing creepage and the specification of resin impregnated paper bushing technology, with a silicone rubber insulator [Eskom, 2009]. The impact these changes can only be assessed with future studies.

Factory assembly related inherited deficiencies in post 1978 manufactured units could be attributed to the impact of expanding power systems due to the increased demand for electricity, when the demand for transformer bushings could also have increased. Accompanying the increase in demand for bushings is the pressure for shorter delivery times, which in turn drives competition in global markets, i.e. faster production with corresponding delivery times. An increase in the production of bushings driven by demand and competition could therefore have introduced errors into manufacture or production processes.

Inherent deficiencies such as inadequate design and manufacturing related problems, coupled with abnormal deterioration in transmission units, featured in the first 15 years in post 1978 manufactured units. Where failure modes could be identified, they were of the mechanical type. According to the literature, approximately 80% of bushing failures in the period 1986 to 1996 (the pre 1986 build) occurred after 10 to 12 years in service, where design deficiencies and aging were typically involved [Sokolov, 1997]. This could suggest that the ability to optimise the bushing design with computer aided techniques introduced unforeseen weaknesses. It further gives an indication that bushings with inherent defects can take time to deteriorate before registering as a failure.

8.3.2. Terminal (Winding Connection) Related Failures

The winding ends (exit leads) are described as one of the critical areas in the transformer when determining the design insulation level [Kulkarni, 2004]. The transformer design insulation level is determined first, before proceeding to the actual design of the insulation system [Kulkarni, 2004].

Inherent deficiencies (inadequate design) were a major contributor of terminal (winding connections) related failures in GSUs. These failures occurred in units from 14 years, were predominantly thermal mode failures and from one manufacturer.

This could suggest that the introduction of computer aided techniques to optimise the transformer design had no impact on the improving reliability of the sample of post 1978 manufactured transformers. This also gives an indication that post 1978 manufactured transformers could operate with inherent deficiencies for a period of time (in this case 14 years) before failure.

8.3.3. Tap Changer Related Failures

Tap changers were among the major contributors of failure in substation and autotransformers, irrespective of manufacturing period. From the surveyed literature in chapter 3, the only major development in tap technology was the move from the oil type to vacuum type in the early 2000's. The tap changers from both manufacturing periods were of the oil type, supporting the fact that there has been no change in tap changer reliability.

Tap changer related failures in post 1978 manufactured transmission transformers were mostly due to inherited (improper maintenance, repair and factory assembly) and inherent deficiencies (design and manufacturing), and had their onset from 4 to 5 years.

With human intervention and the nature of the tap changer maintenance, it is possible that foreign particles or items may find their way into the diverter tank. Switching operations take place in the diverter tank, and the foreign items could result in flashovers, compromising the tap changer operation.

The other two prominent inherited deficiencies (improper repair and factory assembly) also suggest that tap changers are sensitive to movement, handling and human intervention, due to the mechanical nature of their operation.

The abovementioned factors involved human intervention. Eskom has recently moved to this new technology to reduce maintenance activities on tap changers, and ultimately to reduce human intervention. Apart from the reduction in human intervention, maintenance activities require outages and can be costly, so reduction in maintenance also has a financial advantage. The impact of the vacuum technology on tap changer reliability can only be assessed in future studies.

Tap changers were among the minor contributors to power station transformer failures. On-load tap changers allow voltage regulation of transformers by varying the transformer ratio under load, without interruption. The lower contribution in power station transformer failure in units from both manufacturing periods (in particular GSUs) was thus expected, since they are not at the regulating end of the power network, as with distribution and transmission transformers.

8.3.4. Winding Related Failures

According to the surveyed literature, winding related failures featured as a major contributor, irrespective of transformer application and manufacturing period. The same observation was made with the pre and post 1978 manufactured transformers. This could suggest that developments related to the windings have not improved the reliability.

The results have shown that reliability of post 1978 manufactured transformers was affected by system events. As discussed in chapter 3, the rate of power system expansion was much steeper from 1970's. The increased demand for electricity resulted in the addition of more generating capacity and interconnections in power systems, which contributed to an increase in short circuit capacity of networks, i.e. higher fault currents [Kulkarni, 2004].

Failures due to system events occurred predominantly in the North Eastern region on the transmission network, a region historically known to be prone to system events. If a transformer experiences a number of system events over a time period, the winding insulation weakens (prematurely ages or abnormally deteriorates). With subsequent system events, the insulation can be damaged to such an extent that the winding conductors make contact, resulting in a short circuit between turns, or a flashover between windings, resulting in failure of the transformer.

In the sample of distribution transformers, one manufacturer contributed to the majority of the failures in the first 10 years. No failure causes were available but this could suggest design related problems. In GSUs, winding related failures were also predominantly design related.

A typical design problem related to the winding design is insufficient short circuit strength. Short circuit strength enables a transformer to survive through the through-faults due to external short circuit currents in the power system [Kulkarni, 2004]. The effects of short circuit currents on transformers fall into thermal and mechanical effects [Heathcote, 1998]. The thermal effects are caused by the increase in the temperature of the winding conductors. Should the temperature increase remain within the allowable temperature of the conductor, the thermal effects can be seen in the degradation of the winding insulation. The mechanical effects arise from the forces associated with the short circuit currents, where inadequate short circuit strength may lead to mechanical collapse of the windings, deformation or damage to the clamping structure [Kulkarni, 2004].

The distribution sample also indicated a regional significance, where failures above 10 years occurred predominantly in the Eastern region, a coastal region with high humidity.

Aging factors such as water, oxygen, oil products, and particles of different origin, can significantly shorten a transformer's life under the impact of thermal, electric, electromagnetic and electro-dynamic stresses [Cigré WG A2.18, 2003]. Sources of water contamination include residual moisture, atmospheric moisture ingress, decomposition of cellulose and oil aging.

The mid-life winding related failures therefore could be attributed to the effects of accelerated paper insulation aging due to atmospheric moisture ingress in the highly humid region; under the impact of operational stresses, the weakened paper insulation may have been damaged, resulting in inter-turn short circuits between the winding conductors.

8.3.5. Magnetic Circuit (Core) Related Failures

The impact of constant developments in core material and manufacturing discussed in chapter 3 are evident in the contribution of core related problems by manufacturing period, where they featured as a minor contributor in units from both manufacturing periods of substation and autotransformers and in pre 1978 manufactured power station transformers.

Although the results indicate improved reliability of the core with constant developments in technology and manufacturing, the following reasoning could suggest otherwise:

- Winding related failures were among the major contributors for both manufacturing periods; the surveyed literature in chapter 2 also indicated the same result.
- According to the surveyed literature in chapter 3, the pre 1970 core problems related to design and manufacturing, which affected other parts of the transformer (windings and main tank). This essentially makes the core the initiator of the failure.
- It is further questionable whether an optimised core design using computer aided design techniques in the post 1978 period could have impacted on the windings, i.e. what is actually a core design problem develops and is seen as failure related to the windings.
- This suggests that the contributions of winding and core related failures of units from both manufacturing periods could have differed, if failure had initially been identified as a core related problem.

8.3.6. Other Accessories

'Other accessories' were a major contributor in pre 1978 manufactured substation and autotransformers, but not in the post 1978 sample.

Bossi [1983] did not explain what items were classified under 'other accessories'. It will therefore be assumed that 'other accessories' includes the cooling system, as with the post 1978 manufactured transformers. According to the literature in chapter 3, Doble Engineering [2006] indicated that failures related to the cooling system were less likely to lead to failure, which contradicts the findings of Bossi [1983], under aforementioned assumption The cooling system related failures could also have contributed to the winding related failures seen in pre 1978 manufactured units.

In the post 1978 sample, other accessories referred to failures that developed in the cooling system, due to maintenance and repair related inherited deficiencies; the failure mode was predominantly of the mechanical type. This could suggest that human intervention which is required during maintenance and repair impacted on the reliability of the cooling system in post 1978 manufactured transformers.

Although not a major contributor in post 1978 manufactured transformers, failures related to the cooling system could have had an impact on the winding related failures.

8.3.7. Possible Factors Affecting Results and Interpretation

The inference drawn on the reliability of components discussed in section 8.3.1 to 8.3.6 could have differed, due to the following factors:

- Bushings are often kept as spares to replace failed ones. Because transformer failures were based on transformer age at failure and year of manufacture, the possibility exists that a post 1978 manufactured transformer was fitted with a pre 1978 manufactured bushing (resin bonded paper types and the oil impregnated paper types), which had known weaknesses discussed in chapter 3.
- Some of the failures were left unclassified due to the lack of failure investigation reports.
- The failures classification was based on information extracted from the available failure investigation reports. The possibility that investigations identified failure locations, causes and modes incorrectly, can also not be excluded.
- The pre and/or post 1978 failures may have been incorrectly classified in the failures database.
- Damage seen in a certain location does not guarantee that it is the actual initiator of the failure (applies to units from both manufacturing periods).
- There could exist unknown pre and/or post 1978 failures that did not form part of the samples during the analysis.
- If the results in Bossi [1983] had contained failure cause and mode classification for each of the failure locations.
- The pre 1978 results from Bossi [1983] were from 13 countries with different operating and maintenance philosophies, network and environmental conditions, specification of transformers, which could have impacted on the results. If a true comparison of bushing reliability, under the same network, operating and maintenance conditions were possible (meaning the availability of South Africa's pre 1978 manufactured transformer failure data), more meaningful results could have been extracted.

8.4. STATISTICAL ANALYSIS

8.4.1. Applicability/Relevance to Transformer Data

Only complete failures showed agreement with the expected hazard function interpretation, when using both CD and MCD analysis with the HP method.

The fact that failures with repair showed no significance could suggest that repair has an impact on analysis, confirming the uncertainty around the treatment of such data discussed in chapter 6.

Factors that could have affected the outcomes of the statistical analysis assessment include:

- Incorrect development (and extension), and application of the theory.
- Incorrect classification of transformer failures which led to hazard function interpretation not agreeing.

Further investigation and discussion on the applicability of the statistical analysis methods to the transformer data are not within the scope of this dissertation.

8.4.2. Trends According to Manufacturing Period

The only significant observation that could be made when these trends were analysed as CD and MCD using the HP method, was in terms of the onset of increasing IFRs; the onset of increasing IFRs occurred earlier in post 1978 than in pre 1978 manufactured units.

Further comparison of the trends in reliability related to manufacturing period (pre and post 1978) could not be made, because the available data which was needed to assess the expected interpretation, consisted only of post 1978 manufactured transmission transformers.

8.5. SUMMARY

This chapter was aimed at identifying the trends in reliability/failure of transformers, and correlating them with changes in transformer design, manufacture and technology, or other factors that could have impacted on the reliability.

The next chapter will assess whether the dissertation hypothesis is valid based on the main results.

CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS

9.1. TRENDS IN RELIABILITY ACCORDING TO MANUFACTURING PERIOD

Two manufacturing periods were identified as being significant in terms of developments in design, manufacture and technology, and the available failure statistics. Acknowledging the constraints discussed sections 2.4.1, 3.1, and 5.5, the following trends were found to be the most significant.

9.1.1. AAFR & IFR According to Manufacturing Period

Lower reliability of post 1978 manufactured transformers with higher voltage ranges could be attributed to the introduction of computer aided design techniques and increasing competition in the global market, which ultimately resulted in the margin between withstand levels and operating stress levels of transformers being reduced. The onset of increasing IFRs in transmission transformer failures occurred earlier in transformer life in post 1978 than in pre 1978 manufactured units, and could also be attributed to the same causes.

Accessories such as bushings and tap changers made significant contributions to failure of post 1978 manufactured units, and their failures also contributed to the higher AAFR. The bushing and tap changer technologies were the same in both manufacturing periods.

9.1.2. Terminal (Bushing) Reliability

Based on the major contributions of bushing related failures, post 1978 reliability was affected by the following:

- Technology: To a large extent reliability was affected by the technology used at the time: the external porcelain insulator. A new insulating medium which eliminates the weakness of the porcelain insulator was introduced in the 2000's and implemented in Eskom in the late 2000's. The reliability of the new bushings can only be assessed in future studies.
- Manufacturing/Power System Expansion: Manufacturing or production related errors could have been introduced due to the increased bushing production, resulting from increased demand for bushings, and increasing competition in global markets.

- Design Techniques: The ability to optimise the bushing design with computer aided design techniques could have introduced unanticipated inherent weaknesses.

The porcelain insulator was used in the pre 1978 period, but poorer post 1978 reliability could also be attributed to increased industrial pollution due to increasing industries (mining, fossil fuelled power generation, industrial factories etc.).

9.1.3. Tap Changer Reliability

Low tap changer reliability has also been shown to be related to the technology used in both manufacturing periods: oil type tap changers. In the late 2000's the vacuum tap changer technology was introduced, which eliminates contamination of the oil, thereby extending maintenance intervals and decreasing the frequency of human intervention. The impact of bushing reliability with the new technology can only be assessed in future studies.

9.1.4. Core Reliability

The impact of constant developments in core material and manufacturing was evident in the contribution of core related problems, where it featured as a minor contributor, irrespective of manufacturing period.

9.1.5. Terminal (Winding Connections) Reliability

Inadequate design was a major contributor of terminal (winding connections) related failures in post 1978 manufactured GSUs, suggesting that the introduction of computer aided techniques to optimise the transformer design did not improve reliability.

9.1.6. Reliability of 'Other Accessories'

In the post 1978 sample, 'other accessories' were failures that developed in the cooling system due to maintenance and repair related inherited deficiencies; the failure mode was predominantly of the mechanical type. This could suggest that human intervention impacted on the reliability. Although not identified as a major contributor in post 1978 manufactured transformers, failures related to the cooling system could have had an impact on the winding related failures in this period.

It was assumed that 'other accessories' in the pre 1978 manufactured transformers included the cooling system. The contribution of cooling system related failures could also have contributed to the winding related failures seen in pre 1978 manufactured units.

9.1.7. Winding Reliability

Pre 1978 winding reliability was influenced by the following factors:

- Power System Expansion: resulting from the increased demand for electricity, which is associated with higher fault currents. Numerical design techniques used at the time were not effective in determining abnormal service conditions.
- Drying of Windings: Could have resulted in a loss of clamping pressure, and reducing short circuit withstand strength.
- Core Design Problems: Pre 1970 core problems related to design and manufacturing could have affected other parts of the transformer, such as the windings.
- Cooling system problems possibly resulted in overheating of windings (refer to section 9.1.6)

Evaluation of the South African data and surveyed literature revealed that post 1978 winding reliability was affected by the following factors:

- System Events: The increased demand for electricity (much steeper from the 1980's) resulted in the addition of generating capacity and more interconnections in power systems, which resulted in much higher fault currents.
- Insufficient Modelling of Abnormal Service Conditions: Although the introduction of computer aided design allowed modelling of the abnormal service conditions of transformers, the higher fault currents resulting from system events may have been miscalculated (underestimated), reducing the short circuit withstand.
- Reduction in Design Insulation Margins: Resulting from computer aided design techniques and competition increase in global markets.
- Optimised Core Design: Optimising the core design using computer aided design techniques in the post 1978 period could have impacted on the windings' diminishing reliability.

- Regional Characteristics/Environmental Factors: Regional network characteristics (system events) and environmental factors (high humidity) contributed to winding failures, but do not appear to have been significantly different pre- and post 1978.

9.2. COMPARING RELIABILITY IN SOUTH AFRICA WITH OTHER COUNTRIES

Comparing transformer reliability in South Africa with the experience of other countries was constrained by factors discussed in section 2.4.1, in particular the limited publicly available survey results, the definition of failure, methods of calculating failure rates, and classification of failures (failure locations, causes and modes). Despite the constraints, the following were observed:

- No significant differences in terms of failures classification,
- AAFR remained within the industry benchmark of 2%,
- AAFR increased with increasing voltage for transformers above 100kV, although not the case in Sokolov [2005-1],
- Increasing IFR with age for tap changer related failures,
- Increasing IFR with age for transformer failures.

9.3. APPLICABILITY OF STATISTICAL ANALYSIS TO TRANSFORMER DATA

The data consisted of transformers with failures with repair, and some had multiple failures with repair. The fact that ‘failures with repair’ showed no apparent significance could suggest that repair has an impact on statistical analysis, confirming the uncertainties around the treatment of such data discussed in chapter 6.

Further investigation and discussion of the applicability of the statistical analysis methods to the transformer data are not within the scope of this dissertation.

9.4. VALIDITY OF HYPOTHESIS

It was hypothesised that the reliability of older transformer designs could be shown to be significantly different from that of newer designs and that this is a result of the differences in design, manufacture and technology during different periods.

The following trends in reliability (failure) with manufacturing periods, supports the hypothesis:

- The AAFR indicated lower reliability of post 1978 manufactured transformers with higher voltage ranges, which could be attributed to the introduction of computer aided design techniques and increasing competition in the global market. These two factors ultimately resulted in the margin between withstand levels and operating stress levels of transformers being reduced. The IFR indicated that the onset of increasing failure rates occurred earlier in post 1978 manufactured transformers than in pre 1978 manufactured units, and could be attributed to the same reasons. However, accessories such as the bushings and tap changers made significant contributions to the failure of post 1978 manufactured units (tap changers also in pre 1978 manufactured units), and their failures also contributed to the higher AAFR of post 1978 manufactured units. The bushing and tap changer technologies were the same in both manufacturing periods, demonstrating the converse of the hypothesis: that there were no significant differences in reliability because there were no developments in technology.

- Terminals (bushings) were a major contributor to failures in post 1978 manufactured substation transformers and autotransformers, but not in pre 1978 manufactured units. Although the bushing statistics were significantly different according to manufacturing period, the bushing technology (the porcelain insulator) which was identified as the main weakness, did not change with manufacturing period. Lower reliability of the post 1978 bushings could be attributed to increased industrial pollution due increasing industries (mining, fossil fuelled power generation, industrial factories etc.), and its negative effect on bushings (as discussed in chapter 3). Other factors affecting bushing reliability in this period were manufacturing/power system expansion, and computer aided design.

- Constant development in core technology and manufacturing resulted in there being no differences in reliability according to manufacturing period, with high reliability being maintained. However, core design in the pre and post 1978 periods has been suspected of contributing to winding related problems in both periods. The reliability statistics on the other hand do not indicate this.

The following trends in reliability (failure) with manufacturing period, partially support the hypothesis:

- 'Other accessories' was a major contributor to failure in pre 1978 manufactured unit, substation and autotransformers, but not in post 1978 units. Although it was assumed that 'other accessories' in the pre 1978 manufactured transformers included the cooling system, the contribution of cooling system related failures could have shown in the winding related failures seen in pre 1978 manufactured units. No failure causes or modes were provided at failure location level in Bossi [1983], and no known developments in design, manufacture or technology were located in the surveyed literature.

Trends in reliability have shown that the hypothesis is supported by some results and partially supported by others. Where high reliability was maintained in units from both manufacturing periods, it was attributed to constant developments in technology and manufacture. Where low reliability was maintained in units from both manufacturing periods, it was attributed to lack of developments in technology. Where reliability differed, the older designs appeared to be more reliable.

In summary, the hypothesis was found to be partially valid, but not in the sense that the overall reliability of groups of transformers could be predicted from a knowledge of their year of manufacture. Changes in design methods, materials, manufacturing details and the environment have affected the reliability of transformer components in different ways and the overall reliability does not appear to have changed much. There is insufficient data from recently manufactured transformers to establish the effects of the most recent technology developments on the reliability. Further, the analysis has shown that confounding factors such as repair might affect the apparent reliability if not accounted for rigorously.

9.5. RECOMMENDATIONS

Proving the validity of the hypothesis was to a large extent constrained by factors discussed in sections 2.4.1, 3.1, and 5.5. The most significant constraints included the unavailability of reliability statistics, definition of failure, identification of the manufacturing period, and classification of failures. It is therefore recommended that future data collection for reliability studies include:

- Failure cause and mode classification at failure location level,
- Clear definitions of transformer failure,
- Clear descriptions of the manufacturing periods of the transformers,
- Uniform methodologies for calculations such as failure rate,

The fact that 'failures with repair' showed no apparent significance could suggest that repair has an impact on statistical analysis, confirming the uncertainties around the treatment of such data discussed in chapter 6. Further investigation of the applicability of the commonly used statistical analysis methods to transformer failure data is not within the scope of this dissertation, and is a topic recommended for further research.

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APPENDIX A: DEFINITIONS FROM SURVEYS AND INTERNATIONAL STANDARDS AND GUIDELINES

SOURCE	TYPE	DEFINITION
[IEC, 1990]	Failure	The termination of the ability of an item to perform a required function.
[Bossi, 1983]	Failure	Lack of performance by a transformer of its required functions so that the unit must be taken out of service to be repaired.
[IEEE, 1986]	Failure	The termination of the ability of a transformer to perform its specific function.
[Cigré WG A2.18, 2003]	Failure	Any situation which requires the equipment to be removed from service for investigation.
[Kogan, 1988]	Failure	Any forced outage of a transformer due to its failure in service. Trouble which requires transformer to be returned to a factory for repair, or which requires extensive field repair. Transportation damage and minor troubles which may require an equipment outage are not considered as failures.
[Higgins, 2001]	Minor Failure	Can be repaired quickly in situ. The resulting outage typically would be less than one month.
[Higgins, 2001]	Major Failure	Must be repaired (if this is possible) off-site, usually at manufacturers' works. The resulting outage typically would be measured in months. Failures in which the transformer is destroyed or must be retired are also major failures.
[Bossi, 1983]	Failure with scheduled outage	Failure for which the transformer can deliberately be taken out of service at a selected time.
[Bossi, 1983]	Failure with forced outage	Failure for which the transformer must be taken out of service immediately (within 30 minutes).
[IEEE, 1986]	Failure with forced outage	Failure of a transformer that requires its immediate removal from service. This is accomplished automatically or as soon as switching operations can be performed.

SOURCE	TYPE	DEFINITION
[IEEE, 1986]	Failure with scheduled outage	Failure for which a transformer must be taken deliberately out of service at a selected time.
[Cigré, WG A2.18, 2003]	Failure with forced outage	Failure of an equipment that requires its immediate removal from the system. This is accomplished either automatically by the operation of protection equipment or as soon as switching operations can be performed.
[Cigré, WG A2.18, 2003]	Failure with scheduled outage	Failure for which the removal of the equipment from service can be deferred to some more convenient occasion, but still requires a change to planned outage programme.
[IEC, 1990]	Fault	The state of an item characterised by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to the lack of external sources.
[Cigré, WG A2.18, 2003]	Fault	Any deterioration beyond normal wear or aging.
[IEEE, 1986]	Defect	Imperfection or partial lack of performance that can be corrected without taking the transformer out of service.
[Bossi, 1983]	Defect	Imperfection in the state of a transformer or partial lack of performance that may be eliminated without taking the transformer out of service, or on the occasion of ordinary and detailed servicing.
[Cigré, WG A2.18, 2003]	Defect	Any non conformance to normal condition requiring some investigative or remedial action.
[Bossi, 1983]	Failure Rate	The ratio of the number of transformers that failed over a certain number of years, to the number of transformers in service during those years.
[IEEE, 1986]	Failure Rate	The ratio of the number 'failures with forced outages' of a given population over a given period of time, to the number of accumulated service years for all transformers in that population over the same period of time.
[Kachler, 2001]	Failure Rate	The ratio of the number of failures or number of units failed from N units in service, to the number of service years accumulated with N units in service, where N is the number of units in service in a 10 year period.