

**FINAL REPORT OF THE SECOND
INTERNATIONAL ENQUIRY ON HIGH
VOLTAGE CIRCUIT-BREAKER FAILURES
AND DEFECTS IN SERVICE**

**Working Group 06 (Reliability of HV circuit-breakers)
of Study Committee 13 (Switching Equipment)**

June 1994



FINAL REPORT OF THE SECOND INTERNATIONAL ENQUIRY ON HIGH VOLTAGE CIRCUIT-BREAKER FAILURES AND DEFECTS IN SERVICE

by
A.L.J.Janssen, W.Degen, Ch.R.Heising, H.Bruvik,
E.Colombo, W.Lanz, P.Fletcher, G.Sanchis
of
CIGRE WG 13.06 (Reliability of HV circuit-breakers)
and published at the request of the Chairman of SC 13

June 1994

FOREWORD

This report gives the results of the Second International Enquiry on circuit-breaker failures and defects in service, observed during a period of four years (1988-1991). A summary of the results has been presented as a separate report at the CIGRE-session in Paris in 1994 [11]. This summary is attached as appendix E.

Chapter 2 of this report gives details of the organisation of the enquiry and presents the main tables of data derived from it. Chapter 3 to 9 give the results of analysis of data under several main subject headings. Each of these chapters can be read, in conjunction with Chapter 1 (Introduction), as a separate report. As a consequence, some introductory notes will be repeated several times.

Chapter 10 gives the results of data analysis concerning five special subjects and Chapter 11 gives recommendations for other surveys. The conclusions of the Second International Enquiry are detailed in Chapter 12.

Four publications of CIGRE WG 13.06 are added as appendices.

CONTENTS

	Page:		Page:		
1.	INTRODUCTION.....	9	7.	DIAGNOSTIC TECHNIQUES.....	95
2.	GENERAL RESULTS.....	11	8.	IMPACT ON TESTING TO IMPROVE RELIABILITY.....	97
2.1	Objectives of the Second Enquiry.....	11	8.1	Introduction.....	97
2.2	Scope.....	11	8.2	Objectives and classification of testing.....	98
2.3	Definitions.....	12	8.3	Impact of different test duties.....	100
2.4	Organization of the survey.....	12	8.4	Identification of critical sub-assemblies.....	102
2.5	Questionnaire.....	12	8.5	Identification of critical failure modes and failure causes.....	105
2.6	Participation.....	13	8.6	Comparison to the First Enquiry.....	107
2.7	Population.....	14	8.7	Mechanical endurance tests.....	110
2.8	Data processing.....	16	8.8	Conclusions.....	111
2.9	Failures and failure rates.....	17	9.	RELIABILITY DATA FOR USE IN SUBSTATION AND SYSTEM STUDIES....	113
2.10	Other tables and evaluations.....	31	10.	SPECIAL ITEMS.....	115
2.11	Reliability of the data.....	43	10.1	Low temperatures.....	115
3.	IMPACT OF THE TYPE OF OPERATING MECHANISM ON THE RELIABILITY.....	47	10.2	Reliability of control circuits.....	115
3.1	Introduction.....	47	10.3	Electrical breakdowns.....	116
3.2	Circuit-breaker drive systems.....	47	10.4	Fires and /or explosions.....	116
3.3	Impact of the drive on the reliability of the circuit-breaker.....	48	10.5	Modifications of circuit-breakers.....	117
3.4	Correlations with the failure modes and causes.....	49	11.	RECOMMENDATIONS FOR OTHER SURVEYS.....	119
3.5	Reliability data.....	53	11.1	Organization.....	119
3.6	Comparison of failures on drives of metal enclosed versus non metal enclosed circuit-breakers.....	55	11.2	Improvement of the population card.....	119
3.7	Impact of environmental conditions and number of operations.....	55	11.3	Improvement of the failure card.....	119
3.8	Necessity of improvements in testing and/or diagnostics.....	58	11.4	Importance of statistics.....	120
3.9	Conclusions.....	58	12.	MAIN RESULTS AND CONCLUSIONS....	121
3.10	References.....	59	13.	ACKNOWLEDGEMENT.....	125
4.	SF ₆ TIGHTNESS AND GAS DENSITY SUPERVISION OF HIGH VOLTAGE CIRCUIT-BREAKERS.....	61	14.	REFERENCES.....	127
4.1	Introduction.....	61	15.	APPENDICES.....	129
4.2	General information.....	61	A	Population card	
4.3	The Second International Enquiry.....	62	B	Failure card	
4.4	The results of SF ₆ tightness.....	62	C	Definitions	
4.5	The results of SF ₆ supervision monitor.....	69	D	List of participating utilities	
4.6	Overall SF ₆ tightness failure rates.....	69	E	A summary of the Final Results and Conclusions of the Second International Enquiry on the Reliability of High Voltage Circuit-Breakers	
4.7	Conclusions.....	72	F	Application of Diagnostic Techniques for High Voltage Circuit-Breakers	
5.	ANALYSIS OF THE COLLECTED DATA WITH REFERENCE TO THE TYPE OF CIRCUIT-BREAKER ENCLOSURE.....	73	G	Diagnostic Techniques for High Voltage Circuit-Breakers and their Application	
5.1	Introduction.....	73	H	Final report on High Voltage Circuit-Breaker Reliability Data for Use in Substation and Sys- tem Studies	
5.2	General information.....	73			
5.3	Failures and defects.....	74			
5.4	Conclusions.....	75			
5.5	References.....	76			
6.	MAINTENANCE.....	87			
6.1	Introduction.....	87			
6.2	Maintenance policies.....	87			
6.3	Impact of maintenance on failures.....	91			
6.4	Conclusions.....	94			

LIST OF FIGURES AND TABLES

Figures:	Page:
General results:	
2.9.1.1	Number of failures per country.....17
2.9.1.2	Failure rates per country..... 17
2.10.1.1	Ratio of mf/MF per country..... 31
Analysis of the collected data with reference to the type of circuit-breaker enclosure:	
5.2.1	Number of metal enclosed circuit-breakers per country.....77
5.2.2	Number of non metal enclosed circuit-breakers per country.....77
Maintenance:	
6.3.1	Occurrence of failures versus number of operating cycles at the time of failure since last overhaul.....91
Impact on testing to improve reliability:	
8.1.1	Revealing of critical sub-assemblies..... 97
8.1.2	Revealing of critical failure modes and failure causes.....98
Tables:	Page:
General results:	
2.7.1	Estimated average number of operating cycles per circuit-breaker-year..... 15
2.7.2	Average interval between scheduled overhaul (years)..... 15
2.7.3	Estimated average labour effort for scheduled overhaul (manhrs/year)..... 15
2.7.4	Estimated average cost of spares for scheduled overhaul (manhrs/year)..... 15
2.9.1.1	Number of circuit-breaker-years in service of all the countries..... 18
2.9.2.1	Major failure rates.....19
2.9.2.2	Minor failure rates..... 19
2.9.2.3	Number of major failures concerning the population of all the countries.....20
2.9.2.4	Number of minor failures concerning the population of all the countries..... 21
2.9.2.5	Failure rates evaluated for different sets of circuit-breakers and associated failures..... 22
2.9.3.1	Condition of the circuit-breaker when the failure or defect was discovered..... 23
2.9.4.1	Identification of the sub-assembly or component responsible for the major failure.....24
2.9.4.2	Identification of the sub-assembly or component responsible for the minor failure..... 24
2.9.5.1	Stress presumed contributing to the failure/defect: Ambient temperature.....25
2.9.5.2	Stress presumed contributing to the failure/defect: Environmental condition.....25
2.9.6.1	Characteristics of the major failures.....26
2.9.6.2	Characteristics of the minor failures.....26
2.9.7.1	Origin of major failures..... 27
2.9.7.2	Origin of minor failures.....27
2.9.7.3	Cause of major failures.....28
2.9.7.4	Cause of minor failures.....28
2.9.8.1	Number of major failures characterized by an electrical breakdown.....29
2.9.8.2	Electrical breakdown failure rates..... 29

	Page:
2.9.8.3	Modes of the major failures having fire and/or explosion as a consequence.....30
2.9.8.4	Causes of the major failures having fire and/or explosion as a consequence..... 30
2.10.1.1	Estimated average number of operating cycles since commissioning until.....31 a major failure occurred
2.10.1.2	Estimated average number of operating cycles since commissioning until.....32 a minor failure occurred
2.10.1.3	Estimated average number of operating cycles since last overhaul until.....32 a major failure occurred
2.10.1.4	Estimated average number of operating cycles since last overhaul until.....32 a minor failure occurred
2.10.2.1	Correlation concerning the origin of failure and the component responsible for the major failure.....33
2.10.2.2	Correlation concerning the origin of failure and the component responsible for the minor failure..... 34
2.10.2.3	Correlation concerning the components responsible for the major failures and its causes.....35
2.10.2.4	Correlation concerning the components responsible for the minor failures and its causes.....36
2.10.2.5	Correlation concerning the components responsible for the major failure.....37 and the mode of the failure
2.10.2.6	Correlation concerning the components responsible for the minor failure.....38 and the mode of the failure
2.10.2.7	Correlation concerning the mode of the major failure and its origin..... 39
2.10.2.8	Correlation concerning the mode of the minor failure and its origin.....40
2.10.2.9	Correlation concerning the mode of the major failure and its cause.....41
2.10.2.10	Correlation concerning the mode of the minor failure and its cause.....42
2.11.1	Major failure rates with some countries excluded.....43
2.11.2	Major failure rates with particular countries excluded.....44
2.11.3	90% confidence limits for number of major failures.....44
2.11.4	Min. and max. estimation of the major failure rate per 100 circuit-breaker-years.....44
2.11.5	Major failure rates per characteristics.....45
2.11.6	Estimated number of operating cycles per year and per lifetime.....46
 Impact of the type of operating mechanism on the reliability:	
3.2.1	Distribution of type of drives for the whole population.....48
3.2.2	Number of circuit-breaker-years for the different voltage levels.....48
3.3.1	Origin of major failures in %.....49
3.3.2	Origin of minor failures in %.....49
3.4.1	Distribution of failures of the different types of operating mechanism versus voltage level.....50
3.4.2	Characteristics of the mechanical major failures versus the different types..... 50 of operating mechanism
3.4.3	Characteristics of the mechanical minor failures versus the different types.....51 of operating mechanism
3.4.4	Cause of mechanical major failures.....51
3.4.5	Cause of mechanical minor failures.....52
3.4.6	Cause of mechanical major failures on different kind of operating mechanism.....52
3.4.7	Cause of mechanical minor failures on different kind of operating mechanism.....53
3.5.1	Mechanical major failure rates for the different types of operating mechanism.....53
3.5.2	Mechanical minor failure rates for the different types of operating mechanism.....54
3.5.3	Rates of mechanical major failures for the different periods of collection.....54
3.5.4	Rates of mechanical minor failures for the different periods of collection.....55
3.5.5	Identification of the sub-assembly or component responsible for the mechanical failures.....55 of the operating mechanism
3.6.1	Comparison of major failure rates of non metal enclosed versus metal enclosed circuit-breakers.....56
3.6.2	Comparison of minor failure rates of non metal enclosed versus metal enclosed circuit-breakers.....56

	Page:
3.7.1	Location of the circuit-breaker concerning the mechanical major failures on operating mechanism..... 56
3.7.2	Location of the circuit-breaker concerning the mechanical minor failure on operating mechanism..... 57
3.7.3	Stress presumed contributing to the mechanical failure or defect: Ambient temperature..... 57
3.7.4	Stress presumed contributing to the mechanical failure or defect: Environmental condition..... 57
3.7.5	Ambient temperature stress presumed contributing to the mechanical failure or defect on operating mechanism..... 58
3.7.6	Estimated average number of operating cycles since commissioning until a major failure occurred..... 58
3.8.1	Condition of the circuit-breaker when the mechanical failure on operating mechanism was discovered..... 59

SF6 tightness and gas density supervision of high voltage circuit-breakers:

4.3.1	Criteria to declare SF6 tightness failures..... 62
4.4.1	Origin of major failures..... 63
4.4.2	Origin of minor failures..... 63
4.4.3	Characteristics of SF6 tightness major failures..... 64
4.4.4	SF6 tightness failures per voltage..... 64
4.4.5	SF6 tightness failures per voltage and for different enclosure technologies..... 65
4.4.6	SF6 tightness failures per voltage and for different locations..... 65
4.4.7	SF6 tightness failures per voltage and for different ages of the circuit-breaker..... 66
4.4.8	SF6 tightness failures according to enclosure technology..... 66
4.4.9	SF6 tightness failures per location and for different enclosure technologies..... 67
4.4.10	SF6 tightness failures per age and for different enclosure technologies..... 67
4.4.11	SF6 tightness failures according to location..... 67
4.4.12	SF6 tightness failures per age and for different locations..... 68
4.4.13	SF6 tightness failures according to age..... 68
4.4.14	Component responsible for SF6 tightness minor failures..... 68
4.4.15	Characteristics of SF6 tightness minor failures..... 69
4.4.16	Origin of SF6 density monitor failures..... 70
4.4.17	Causes of SF6 density monitor failures..... 70
4.6.1	Rates of major failures whose origin is tightness of SF6..... 71
4.6.2	Rates of minor failures whose origin is tightness of SF6..... 71

Analysis of the collected data with reference to the type of circuit-breaker enclosure:

5.2.1	Average interval between scheduled overhauls..... 78
5.2.2	Estimated average labour effort for scheduled overhaul..... 79
5.2.3	Estimated average cost of spare parts consumed for scheduled overhaul..... 79
5.3.1	Failure rates evaluated for different sets of circuit-breakers and associated failures..... 80
5.3.2	Origin of major failures..... 81
5.3.3	Origin of minor failures..... 82
5.3.4	Cause of major failures..... 83
5.3.5	Cause of minor failures..... 84
5.3.6	Characteristics of the major failures..... 85
5.3.7	Characteristics of the minor failures..... 85
5.3.8	Identification of the sub-assembly or component responsible for the major failure..... 86

	Page:
5.3.9	Identification of the sub-assembly or component responsible for the minor failure..... 86
 Maintenance:	
6.2.1	Average interval between scheduled overhaul..... 88
6.2.2	Average interval between scheduled overhaul by location and enclosure type..... 88
6.2.3	Estimated average labour effort for scheduled overhaul..... 89
6.2.4	Estimated average labour effort for scheduled overhaul by location and enclosure type..... 89
6.2.5	Estimated cost of spare parts for scheduled overhaul..... 90
6.2.6	Estimated cost of spare parts for scheduled overhaul by location and enclosure type..... 90
6.3.1	Condition of the circuit-breaker when the failure or defect was discovered..... 92
6.3.2	Responses to Question <i>Cause of failure or defect</i> giving incorrect maintenance as cause..... 92
6.3.3	Component responsible for the failure where the cause was given as incorrect maintenance..... 93
6.3.4	Characteristic of the major failure where the cause was given as incorrect maintenance..... 93
 Impact on testing to improve reliability:	
8.2.1	Examples of test duties..... 99
8.3.1	Correlation between sub-assemblies and tests stressing/qualifying them..... 100
8.3.2	Correlation between failure modes and tests detecting them..... 101
8.4.1	Correlation between sub-assemblies responsible for the failure and the origin of the major failure..... 102
8.4.2	Correlation between sub-assemblies responsible for the failure and the origin of the minor failure..... 103
8.4.3	Estimated average number of operating cycles per circuit-breaker per year and per lifetime..... 103
8.4.4	Correlation between sub-assemblies responsible for the failure and the characteristics of the major failure..... 104
8.4.5	Correlation between sub-assemblies responsible for the failure and the characteristics of the minor failure..... 105
8.5.1	Correlation between the characteristics of the failure and the origin of the major failure..... 106
8.5.2	Correlation between the characteristics of the failure and the origin of the minor failure..... 106
8.5.3	Correlation between breakdown and the causes of the failures..... 107
8.5.4	Correlation between sub-assemblies responsible for the failure and the causes of the major failures..... 108
8.5.5	Correlation between sub-assemblies responsible for the failure and the causes of the minor failures..... 109
8.7.1	Estimated average number of operating cycles since commissioning until a major failure occurred..... 110
8.7.2	Estimated average number of operating cycles since commissioning until a minor failure occurred..... 110
 Special items:	
10.1.1	Ambient temperature stress presumed contributing to the failure or defect..... 115
10.3.1	Electrical breakdown failures and failure rates..... 116
10.4.1	Number of major failures and fire/explosions per failure mode..... 117
10.4.2	Circuit-breaker fire and/or explosion rates..... 117
10.5.1	Number of cases in which other circuit-breakers had to be removed from service after a major failure..... 117

1. INTRODUCTION

One of the most important characteristics of an electrical power system is the quality of service; this depends on the reliability of its equipment, particularly that of the circuit-breakers due to their various and essential duties. The development of networks, the increase of power generation, the rise in service voltages and the increasing importance of interconnections, result in increasing importance being given to the problem of reliability of circuit-breakers. Therefore a subject of great interest is a better understanding of the failures of circuit-breakers, their causes and their consequences as this is a necessary prerequisite for study of the possible courses of action required to ensure adequate service reliability.

In 1970 CIGRE Study Committee 13, in view of the interest in this topic, entrusted Working Group 13.06 "Reliability of Circuit-Breakers" to carry out the necessary studies. This Working Group carried out several studies on the reliability of high-voltage circuit-breakers during the period 1971 to 1985. This work is described in reports [1], [2], [3]. In particular during the period 1974-1977 CIGRE WG 13.06 conducted a worldwide enquiry on circuit-breaker failures and defects in service. The CIGRE WG 13.06 studies to improve reliability were made after the First International Enquiry and are reported in [2], [3]. A complete system of tests covering all circuit-breaker components and stages of evolution such as development, manufacturing, commissioning and maintenance has been described. Special emphasis has been laid on the improvement of the mechanical reliability.

These studies were the basis for new mechanical and environmental tests on circuit-breakers such as mechanical operation tests with an increased number of operations, low and high temperature tests and humidity test. At the same time IEC TC 17A (High Voltage Switchgear and Controlgear) set up Working Group 11 on *Mechanical Problems and Reliability*, which took into account the results of CIGRE WG 13.06. IEC SC 17A also asked WG 11 to develop a proposed guide for collecting failure data on high voltage circuit-breakers. The CIGRE WG 13.06 questionnaire and definitions have been the starting point for the development of this guide [5].

Taking into account the above mentioned considerations CIGRE SC 13 has entrusted WG 13.06 to reinvestigate the different aspects of the problems concerning the reliability of high voltage circuit-breakers, and a new CIGRE WG 13.06 was set up with a new membership to achieve this purpose.

In 1986 the new CIGRE WG 13.06 was requested:

1. To conduct a Second International Enquiry on the reliability of high-voltage circuit-breakers;
2. To study monitoring and diagnostic methods.

The results of the Second International Enquiry on circuit-breaker failures and defects in service should show the reliability change since the first survey and indicate whether additional test requirements are needed in the Standards.

The studies on monitoring and diagnostic methods aimed to reveal their impact on the reliability of operation and to determine adequate maintenance intervals. Such an optimization should result in lower costs and a reduction of the number of failures caused by incorrect maintenance. These studies include all circuit-breaker technologies because there is interest for both new and older circuit-breakers.

The results of the studies are published in separate reports with preliminary results [6], [7], [8] and with final results [9], [10], [11] of the second enquiry.

The members of WG 13.06 are representatives from 21 countries. They are selected from experts of the utilities, manufactures, technical institutes and consultants. @

In this report the following abbreviations may be used:

MF for major failure; mf for minor failure or defect; ME for metal-enclosed; NME for non-metal-enclosed; cb for circuit-breaker; cby for circuit-breaker-year(s).

@ All members of CIGRE WG 13.06 have contributed to the enquiry and the studies by the information they submitted and their participation in the discussions.

The present membership of CIGRE WG 13.06 is: H.Brúvik (NO), E.Colombo (IT), N.Cuk (CA), E.Dialynas (GR), J.Declercq (BE), W.Degen (DE), P.Fletcher (GB), W.Franca (BR), Ch.R.Heising (US), A.L.J.Janssen (NL), O.Karlen(SE), W.Lanz (CH), J.Maaskola (FI), G.Meinders (US), V.Onu (RU), S.Peric (AU), G.Sanchis (FR), J.Sikula (CZ), I.Stahan(YU), E.Thurles (FR), M.Tsuchiya (JP), M.Tudrej (FR), V.Varivodov (CIS), E.Zaima (JP).

The following past members and guests also contributed to this work: A.Bargigia (IT), R.Baumgartner (CH), J.Beierer (DE), P.Botelho Neves (BR), J.Brunke (US), L.Desmoulin (FR), S.Ikeda (JP), M.Ishikawa (JP), R.Jeanjean (FR), R.Michaca (FR), D.Stevens (GB).

2. GENERAL RESULTS

2.1 Objectives of the Second International Enquiry

The main results of the First International Enquiry [1] showed that:

- 70% of major failures were of mechanical origin;
- 19% of electrical origin concerning the auxiliary and control circuits;
- 11% of electrical origin concerning the main circuit;
- 48% of major failures were classified as: *Does not close or open on command*;
- The operating mechanism was the part of circuit-breaker responsible for the highest number of failures (37% of major failures);
- The percentage of major failures in auxiliary interrupters or resistors for circuit-breakers having a rated voltage of 500 kV and higher is of the same order as that on making and breaking units.

The comparison of the results of the Second Enquiry with those of the First Enquiry focused on determining whether real improvements have been made in reliability during the intervening years. In particular:

1. Has an improvement been made in mechanical reliability?
2. Has an improvement been made in the reliability of circuit-breaker open and close operations?
3. What have been the changes in the interval between overhauls and in the labour effort for scheduled overhaul?
4. Has this resulted in a reduction in the number of failures caused by incorrect maintenance?

An additional question was whether new specifications are needed in the IEC standards.

New objectives introduced into the Second Enquiry, concerning the general information on circuit-breaker population under consideration, are:

1. Collect data by type of circuit-breaker mechanism (hydraulic, pneumatic, spring operated).
2. Compare the failure rate during an early period of operation with a later period. This is done by dividing the population into two groups: Those placed in service dur-

ing the period 1.1.1978 to 1.1.1983 and those placed in service between 1.1.1983 and 1.1.1992.

3. Compare the failure rates of circuit-breakers located outdoors and indoors, respectively.
4. Compare the failure rates of metal enclosed circuit-breakers with those of non metal-enclosed.

In addition to that, objectives like the identification of the sub-assembly or component responsible for the failure are important. Moreover knowledge of failure rates, downtime, and failure mode data is an objective to serve system planning studies, system operations and the evaluation of *Life cycle costs*.

2.2 Scope

The Second Enquiry concerns circuit-breakers placed in service between 1.1.78 and 1.1.92. CIGRE WG 13.06 has decided to limit the survey to single-pressure SF₆ circuit-breakers, because almost all the new circuit-breakers purchased by utilities since 1982 are of this type. This trend has been even stronger in recent years.

The survey includes both non metal enclosed and metal enclosed circuit-breakers (dead-tank and GIS). The survey also applies to circuit-breakers using SF₆ gas mixed with other gases (e.g. nitrogen) in order to be able to operate at very low temperatures.

The voltage range considered is not related to the service voltage, as in the first enquiry, but related to the rated voltage of the circuit-breaker. The lower limit is chosen to be a rated voltage of 72.5 kV. At the same time, in order to have results comparable with the first enquiry, circuit-breakers with a service voltage above 63 kV and a rated voltage below 72.5 kV, are included.

These policy decisions were exhaustively examined and discussed by CIGRE WG 13.06, taking into account the information submitted by the majority of the utilities involved in this task.

The survey is limited to the failures and defects, that have occurred in the circuit-breaker itself. Auxiliary

plants, like the pneumatic installation in a substation, or the substations control and protection wiring are not within the scope of the survey. Also failures in other equipment, caused by the circuit-breaker, are not considered; while failures in the circuit-breaker, but caused by other equipment, have been included.

The enquiry did not explicitly consider the current transformers, that are built in dead-tank circuit-breakers. However, failures and defects in those current transformers could be mentioned in the box *Others* under *Identification of the sub-assembly or component responsible for the failure or defect*.

2.3 Definitions

As in the First Enquiry, CIGRE WG 13.06 has established a certain number of definitions applicable to the enquiry on circuit-breaker failures so that a sufficiently clear common language is available to deal efficiently with circuit-breaker reliability. The main definitions are given on each of the two cards (see Appendices A and B) used to collect the enquiry data.

Compared with the First Enquiry, the number of definitions has been reduced to a necessary minimum. The following terms were given with the same definitions as those of the First Enquiry: Failure, Major Failure, Minor Failure and Defect. The following definitions had been reworded because they are not clear in the First Enquiry: overhaul and circuit-breaker downtime.

The definitions applied for the Second Enquiry and for the reports on diagnostic techniques are given in appendix C. It is felt by WG 13.06 that the use of common definitions in the field of reliability studies and the studies on maintenance and diagnostic techniques has to be encouraged.

2.4 Organization of the survey

The data for the enquiry were collected by a special questionnaire, which was designed to give the necessary information without identifying the manufacturer of the equipment involved.

The questionnaire is divided into two parts on two separate cards: the population card and the failure

card. Details of the questionnaire will be discussed in the next chapter.

The collection of enquiry data for each country was made by a national CIGRE representative, who offered help in filling out the questionnaire. He was responsible for organising the collection of data, advising the utilities and providing a link between the utility and data processing centre in all questions concerning the enquiry. The national CIGRE representative could be:

- a member of WG 13.06
- a member of the Study Committee No. 13
- a member of the National Committee of CIGRE.

WG 13.06 also prepared the document: 13-88 (WG06) 04 *General Instructions for the CIGRE Representative* giving the instructions for filling out the questionnaire and submitting data. Each representative also prepared his own appropriate introduction for the utilities in his country.

The questionnaire was to be completed by the utilities. It was recommended that this questionnaire was sent to the relevant manufacturers for comments, in order to improve the accuracy and credibility of the data. A close collaboration between users and manufacturers was also desirable to reach the objectives of the survey.

The official enquiry started on January 1st, 1988 and ended on the December 31st, 1991. The completed cards for a specific year were sent by the utility to the national CIGRE representative before the end of March of the following year. Only one population card was given for each year for each utility. If a utility specified different intervals between scheduled overhauls for circuit-breaker of the same category and voltage this utility supplied this information on separate lines of the population card 13-88 (WG06) 02. One failure card was completed for each failure or defect during the year under consideration. Section 8 of the failure card headed *Other information or Comments* is intended to give additional information on all items recorded as *Other* when there is not enough space on the first side of questionnaire or when the event cannot be adequately described by the standard questions.

2.5 Questionnaire

The questionnaire is divided into two parts on two

separate cards. The first part (CIGRE 13-88 (WG 06)02), given in Appendix A is concerned with general information for statistical analysis on the population of circuit-breaker in service for each rated voltage and for each category for which collection of data applied. The second part of the questionnaire (CIGRE 13-88 (WG06)03), given in Appendix B, is concerned with particular information on each failure recorded during the considered year. This card gives the circuit-breaker identification and history, the identification of the sub-assembly or component responsible for the failure or defect, the stress presumed to have contributed to the failure or defect, the classification of the failure or defect and the consequences of the major failures. This card also includes a space on the back for other information when the event can not be described by the standard questions. This card has been improved compared with the one used in the First Enquiry, taking into account the objectives of the new enquiry and four years experience of the previous enquiry.

Several items have been improved where the corresponding information was difficult to obtain (e.g. the items concerning the identification of the sub-assembly or component responsible for the failure or defect and those concerning the stresses presumed to contribute to the failure or defect). Other items have been amended to make them easier to understand, and consequently to obtain more accurate answers. For example the item *Circuit-breaker in service* as listed on the card of the First Enquiry was not very well understood. Some users considered the circuit-breaker to be in service when it was closed and carrying current, and that when in the open position and energized from one or both terminals, it belonged to the category *Other cases*. Consequently the item *In service* was replaced by *In service or available for service*.

In a few important parts of the questionnaire further details have been added; such as: kind of operating mechanism; detailed classification of the minor failure; distinction between mechanical failure of the operating mechanism and that of other parts of circuit-breaker. Moreover the items concerning the consequences of failure have been reviewed, considering only the major failures. In addition the previous information concerning costs was replaced by information on *Other circuit-breakers to be removed from service in order to prevent same failure*. In order to receive better information the classification of the failure, origin and cause were revised, e.g. distinction has been made between design and manufacture.

Apart from the definitions, as described in 2.3, the population card has been changed for the categories of type of operating mechanisms instead of type of circuit-breaker. Furthermore the population has been extended with a column for the period placed in service; i.e. placed in service before or after 1.1.83.

2.6 Participation

This data evaluation takes into consideration the data received from the second international enquiry until the end of October 1992 concerning the failures and defects of single pressure SF₆ gas circuit-breakers occurred in service during the years 1988 to 1991.

While during the First International Enquiry a total of 102 utilities from 22 countries answered, a total of 132 utilities from the following 22 countries responded to the CIGRE questionnaires of the Second Enquiry:

Australia (5)	Austria (11)
Belgium (5)	Brasil (14)
Canada (1)	"Czechoslovakia" (1)
Finland (18)	France (1)
"Germany" (7)	Italy (1)
Japan (5)	Netherlands (10)
New Zealand (1)	Norway (1)
Paraguay (1)	Rumania (1)
Sweden (6)	Switzerland (9)
United Kingdom (1)	USA (31)
"USSR" (1)	"Yugoslavia" (1)

The number between brackets gives the number of the participating utilities of the country. During the period under consideration not only reorganizations and name changes in and between utilities did take place, but also between nations, as has been indicated with the quotes.

The list of utilities having participated in the enquiry is given in appendix D.

During the four years of the enquiry the participation of the countries and the utilities was changing. At the beginning, in 1988, 114 utilities from 20 countries started to participate. In 1989 still 19 countries with even 115 utilities were contributing. After the first two years the number of countries and utilities was decreasing. In 1990 a number of 95 utilities from 18 countries have delivered data and in 1991 only 67 utilities from 15 countries ended the enquiry.

26.5% of the utilities gave information on failures for four years - the total duration of the enquiry -, 33.3 % gave information for three years, 12.7% delivered data for two years and the remaining 27.5% of the utilities replied on only one year.

2.7 Population

The enquiry applies only to single pressure SF6 gas circuit-breakers placed in service between 1.1.1978 and 1.1.1992 with a rated voltage of 72.5 kV and above (including service voltages of 63 kV and above).

This enquiry covers a population of 70708 single pressure SF6 gas circuit-breaker-years in service in comparison to 77892 circuit-breaker-years of all technology circuit-breakers in the First Enquiry.

This population can be subdivided as follows:

- 24355 circuit-breaker-years or 34.4% with a rated voltage equal to or higher than 63 kV, but less than 100 kV
- 23520 circuit-breaker-years or 33.3% with a rated voltage equal to or higher than 100 kV, but less than 200 kV
- 10933 circuit-breaker-years or 15.5% with a rated voltage equal to or higher than 200 kV, but less than 300 kV
- 9917 circuit-breaker-years or 14.0% with a rated voltage equal to or higher than 300 kV, but less than 500 kV
- 1895 circuit-breaker-years or 2.7% with a rated voltage equal to or higher than 500 kV, but less than 700 kV
- 88 circuit-breaker-years or 0.1% with a rated voltage equal to or higher than 700 kV.

The number of answers concerning the circuit-breakers having a rated voltage higher than 550 kV is very small, and therefore statistical processing for this voltage class is of reduced significance.

From this distribution can be seen that a large part of the circuit-breakers involved has a rated voltage below 100 kV.

The whole population can also be split up into 30400 circuit-breaker-years or 43% of metal enclosed cir-

cuit-breakers, which includes dead tank breakers too. 40308 circuit-breaker-years or 57% are non metal enclosed circuit-breakers.

The majority of all circuit-breakers involved is outdoor located (85.2%) and has the hydraulic type operating mechanism (51.4%).

For better information the circuit-breakers in service were split up into those put into service before 1.1.83 and those after 1.1.83. While 21157 circuit-breaker-years belong to circuit-breakers placed in service between 1.1.78 and 1.1.83, 49551 circuit-breaker-years belong to circuit-breakers placed in service between 1.1.83 and 1.1.92. The average age of the circuit-breakers involved in the second worldwide enquiry is less than 6 years, the maximum is 14 years and the minimum less than 1 year. One should be aware of the limited exposure time of the population, when considering effects like mechanical or electrical endurance. More detailed information about the population can be found in Table 2.9.1.1.

The contribution to the population of the different countries has a wide spread. The three smallest populations were from countries with 10, 111 and 145 circuit-breaker-years, while the three largest populations were from countries with 7297, 15855 and 24690 circuit-breaker-years. (See also chapter 2.8 and 2.11)

For the populations of circuit-breakers special information has been collected such as the estimated average number of operating cycles per year, the average interval between scheduled overhaul, the estimated average labour effort for scheduled overhaul in man-hours per year per circuit-breaker and the estimated average cost of spare parts for scheduled overhaul, also expressed in manhours per year per circuit-breaker. The data per voltage class is given in the Tables 2.7.1 to 2.7.4 on the following page.

In the majority of answers the estimated average number of operating cycles per circuit-breaker-year is less than 80; this means that during 25 years of service 90% of the circuit-breakers operate less than 2000 times and during 40 years less than 3200 times.

Table 2.7.2 shows that the majority has an average interval between scheduled overhaul of about 8 years.

The average costs for the estimated average labour effort, expressed in manhours per year, increase with the voltages. However the voltage level 700 kV and above gives a figure of only 30.4 manhours, which

Table 2.7.1 : Estimated average number of operating cycles per cb-year

Voltage (kV)	Average	10% Percentile	50% Percentile	90% Percentile
All Voltages	42	13	30	76
63 ≤ V < 100	47	24	48	84
100 ≤ V < 200	40	10	25	60
200 ≤ V < 300	39	19	20	55
300 ≤ V < 500	36	13	20	82
500 ≤ V < 700	46	15	44	68
700 ≤ V	25	8	40	45

cb = circuit-breaker

may be related to the restricted number of answers.

The wide spread in average costs of spare parts for scheduled overhaul indicates the poor statistical quality.

Table 2.7.3 : Estimated average labour effort for scheduled overhaul (manhrs/year)

Voltage (kV)	Average	10% Percentile	50% Percentile	90% Percentile
All Voltages	23.9	4.0	16.0	49.7
63 ≤ V < 100	15.3	5.0	15.0	30.0
100 ≤ V < 200	17.4	3.0	12.0	43.0
200 ≤ V < 300	24.8	5.0	15.0	49.7
300 ≤ V < 500	31.0	4.8	18.0	56.0
500 ≤ V < 700	82.0	16.0	57.0	120.0
700 ≤ V	30.4	24.0	32.0	40.0

Table 2.7.2 : Average interval between scheduled overhaul (years)

Voltage (kV)	Average	10% Percentile	50% Percentile	90% Percentile
All Voltages	8.3	5.0	7.9	12.0
63 ≤ V < 100	7.6	4.0	6.0	12.0
100 ≤ V < 200	8.8	5.0	8.5	15.0
200 ≤ V < 300	8.2	4.0	7.9	12.0
300 ≤ V < 500	8.2	4.0	7.0	12.0
500 ≤ V < 700	8.9	6.0	6.0	12.0
700 ≤ V	13.5	10.0	12.0	20.0

Table 2.7.4 : Estimated average cost of spares for scheduled overhaul (manhrs/year)

Voltage (kV)	Average	10% Percentile	50% Percentile	90% Percentile
All Voltages	38.1	2.0	10.0	76.2
63 ≤ V < 100	25.4	2.0	24.0	61.0
100 ≤ V < 200	20.7	2.0	8.0	47.8
200 ≤ V < 300	31.6	1.2	12.0	73.5
300 ≤ V < 500	17.7	1.7	8.0	47.8
500 ≤ V < 700	294.8	40.0	320.0	500.0

2.8 Data processing

ENEL (The Italian Electricity Board) was responsible for the data processing. ENEL also printed the cards for the enquiry in English and French, and assumed the corresponding costs without asking for any contribution from the countries participating in the enquiry. ENEL further undertook to respect the decision of WG 13.06 as regards the publication of the results, namely that: "Only members of the Working Group would have access to the data, that only the Group, and not individual members would give instructions for the data processing and only the Group, in agreement with the Study Committee 13, would authorize the publication of any results".

It was also stated that the failure cards sent to ENEL should not include any information in the section headed *CONFIDENTIAL INFORMATION NOT TO BE SENT TO CIGRE*. This information was only to be written on photocopies of the completed cards, retained by the utilities for their own use. Data collected in the Second Enquiry were kept confidential as was done in the First Enquiry [1]. Only general results are published. The utility or country of origin will not be associated or identified with any of the specific data submitted.

In the First Enquiry, the evaluation of the major failure rate has been based on a part of the whole population, due to the poor response on the minor failures. In the Second International Enquiry such a partition within the population was not necessary, as the response on minor failures seemed to be high enough.

As far as major failures are concerned, the totality of the population of circuit-breakers considered in the enquiry was taken into account, on the assumption that the major failure data were collected in all countries with a high degree of accuracy.

In order to check the influence on the failure rates of

the two countries having the highest and the lowest population of circuit-breakers, it was also decided to process the failure data concerning, on the one hand, the population of all countries and, on the other hand, the population of all countries minus the two countries having, respectively, the highest and the lowest population.

As regards correlations concerning major failures and minor failures the circuit-breaker populations of all the utilities or of all countries taking part in the enquiry were considered, taking into account the assumptions made above.

In any case, the results given in the following sections, especially the failure distributions, do change with the same amount as with the First Enquiry, when considering the major failures and minor failures, relating to all countries minus the two countries having the greatest and smallest populations. Those changes are regarded as not significant in the context of such an enquiry and therefore no detailed evaluations based on all countries minus the two countries with the extreme populations are presented in this Technical Brochure.

It should be noted that there are some extreme values regarding the answers to the enquiry, which are difficult to explain, but may correspond to special cases. More detailed information will be given in Chapter 2.11.

Another problem is that of the zero's and the blanks on the population cards, when considering the estimated average period between scheduled overhaul, the estimated costs of labour and the estimated costs of spare parts for scheduled overhaul. Statistical analysis has been performed considering the zero's as well as disregarding the zero's. The evaluation of the results based on the analysis when disregarding the zero's seems to be more consistent and is therefore referred to in this report.

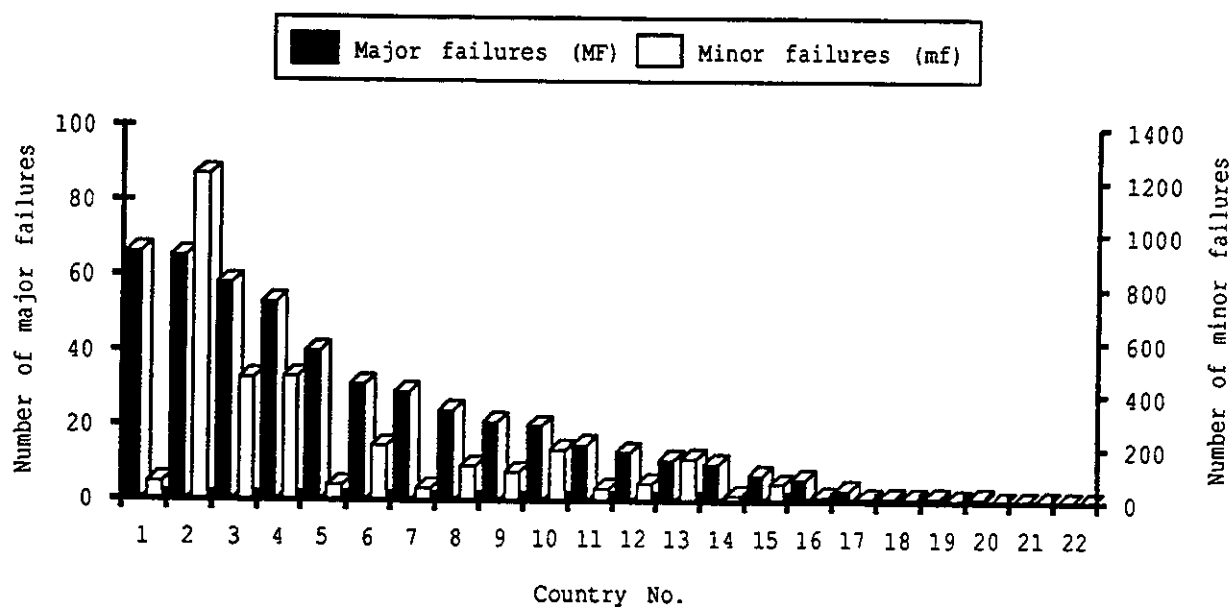
2.9 Failures and failure rates

2.9.1 General figures and tables

General information about the distribution of failures and failure rates among the participating countries is given in Fig. 2.9.1.1 and 2.9.1.2. Especially for the minor failures the spread is rather high. It is also evident that the ratio of mf/MF varies strongly. The

reader has to note, that the order of countries is not identical for Fig. 2.9.1.1 and for Fig. 2.9.1.2. For both figures the order is such that the number and the rate of major failures respectively is decreasing by the number of countries. As a basis for all calculations of failure rates, concerning the total population, Table 2.9.1.1 represents the whole population with all its relevant sub-groups for which the questionnaire asked for.

**Fig. 2.9.1.1 : Number of failures per country
Years 1988-1991**



**Fig. 2.9.1.2 : Failure rates per country
Years 1988-1991**

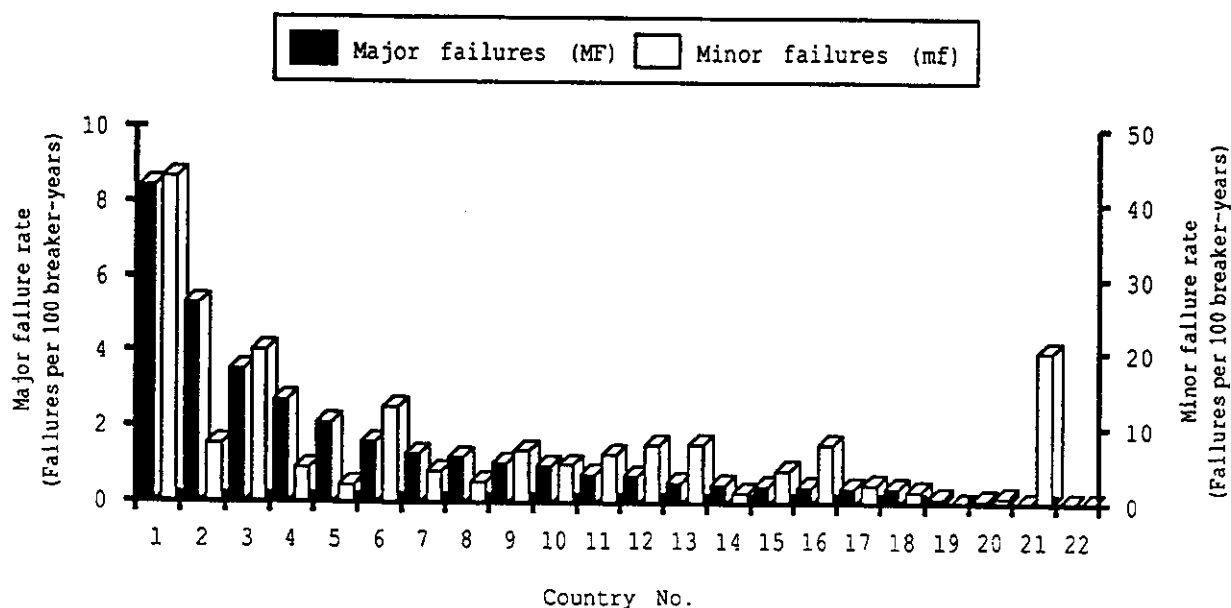


Table 2.9.1.1 : Number of circuit-breaker-years in service of all the countries for each rated voltage and for each category for which collection of data applies

Voltage (kV)	Circuit-breaker placed in service	Location Indoors						Location Outdoors						Sub Totals	Totals	
		Metal enclosed			Non metal enclosed			Metal enclosed			Non metal enclosed					
		Type of operating mechanism			Type of operating mechanism			Type of operating mechanism			Type of operating mechanism					
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C		
63 ≤ V < 100	1.1.78 - 1.1.83	111	796	48	42	809	17	380	3414	636	153	543	108	7057		
	After 1.1.83	583	733	510	19	417	181	2403	2288	4284	4838	678	364	17298	24355	
100 ≤ V < 200	1.1.78 - 1.1.83	615	265	314	82	12	12	234	1000	132	1981	1015	703	6365		
	After 1.1.83	833	797	650	229	70	67	845	1405	336	6229	1898	3796	17155	23520	
200 ≤ V < 300	1.1.78 - 1.1.83	18	28	18	0	0	0	226	336	0	2548	328	13	3515		
	After 1.1.83	85	115	0	110	25	0	198	399	27	5099	974	386	7418	10933	
300 ≤ V < 500	1.1.78 - 1.1.83	450	217	0	38	4	0	500	499	3	1454	267	30	3462		
	After 1.1.83	452	130	25	222	100	9	1561	241	21	2517	803	374	6455	9917	
500 ≤ V < 700	1.1.78 - 1.1.83	33	0	0	0	0	0	223	269	0	201	29	0	755		
	After 1.1.83	185	15	0	9	0	0	320	191	0	296	120	4	1140	1895	
700 ≤ V	1.1.78 - 1.1.83	0	0	0	0	0	0	3	0	0	0	0	0	3		
	After 1.1.83	0	0	0	0	0	0	0	0	0	57	28	0	85	88	
	Subtotals	3365	3096	1565	751	1437	286	6893	10042	5439	25373	6683	5778		70708	
	Totals	8026						22374						37834		
	Σ A Mechanism	36382														
	Σ B Mechanism	21258														
	Σ C Mechanism	13068														

A: Hydraulic mechanism, which may include spring

B: Pneumatic mechanism, which may include spring

C: Spring operated mechanism

2.9.2 Population groups and voltage classes

The Tables 2.9.2.1 through 2.9.2.4 represent an over all basic set of failure rates and failures for all voltage classes and for all the different population groups. By using Table 2.9.1.1, which is the basic population table, and Tables 2.9.2.3 and 2.9.2.4 the calculation of the failure rate for every particular sub-group is possible.

Table 2.9.2.5 gives very interesting information about different sets of circuit-breakers, different sub-populations and associated failure rates.

Table 2.9.2.1 : Major failure rates

Voltage (kV)	Placed in service 1.1.78-1.1.83			Placed in service after 1.1.83			All period		
	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years
All voltages	21157	119	0.562	49551	356	0.718	70708	475	0.672
63 ≤ V < 100	7057	11	0.156	17298	56	0.324	24355	67	0.275
100 ≤ V < 200	6365	37	0.581	17155	123	0.717	23520	160	0.680
200 ≤ V < 300	3515	29	0.825	7418	60	0.809	10933	89	0.814
300 ≤ V < 500	3462	37	1.069	6455	83	1.286	9917	120	1.210
500 ≤ V < 700	755	5	0.662	1140	30	2.632	1895	35	1.847
700 ≤ V	3	0	0.000	85	4	4.706	88	4	4.545

cb = circuit-breaker

Table 2.9.2.2 : Minor failure rates

Voltage (kV)	Placed in service 1.1.78-1.1.83			Placed in service after 1.1.83			All period		
	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years
All voltages	21157	1132	5.350	49551	2226	4.492	70708	3358	4.749
63 ≤ V < 100	7057	98	1.389	17298	444	2.567	24355	542	2.225
100 ≤ V < 200	6365	417	6.551	17155	701	4.086	23520	1118	4.753
200 ≤ V < 300	3515	291	8.279	7418	471	6.349	10933	762	6.970
300 ≤ V < 500	3462	300	8.666	6455	470	7.281	9917	770	7.764
500 ≤ V < 700	755	26	3.444	1140	129	11.316	1895	155	8.179
700 ≤ V	3	0	0.000	85	11	12.941	88	11	12.500

cb = circuit-breaker

Table 2.9.2.3 : Number of major failures (MF) concerning the population of all the countries for each rated voltage and for each category for which collection of data applies

Voltage (kV)	Circuit-breaker placed in service	Location Indoors						Location Outdoors						Sub Totals		
		Metal enclosed			Non metal enclosed			Metal enclosed			Non metal enclosed					
		Type of operating mechanism			Type of operating mechanism			Type of operating mechanism			Type of operating mechanism					
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C		
63 ≤ V < 100	1.1.78 - 1.1.83	0	1	0	0	0	0	3	1	2	2	2	2	2	11	
	After 1.1.83	1	1	2	0	0	0	0	2	23	4	56	67			
100 ≤ V < 200	1.1.78 - 1.1.83	6	1	0	0	0	2	2	0	14	7	5	37			
	After 1.1.83	1	0	4	1	0	2	7	2	58	17	31	123	160		
200 ≤ V < 300	1.1.78 - 1.1.83	0	0	0	0	0	1	2	0	23	3	0	29			
	After 1.1.83	0	1	0	0	1	5	7	0	21	15	10	60	89		
300 ≤ V < 500	1.1.78 - 1.1.83	4	4	0	0	0	3	0	0	24	2	0	37			
	After 1.1.83	7	1	0	0	0	8	7	0	33	14	13	83	120		
500 ≤ V < 700	1.1.78 - 1.1.83	0	0	0	0	0	0	0	0	5	0	0	5			
	After 1.1.83	8	0	0	0	0	0	1	0	14	7	0	30	35		
700 ≤ V	1.1.78 - 1.1.83	0	0	0	0	0	0	0	0	0	0	0	0			
	After 1.1.83	0	0	0	0	0	0	0	0	0	4	0	4	4		
	Subtotals	27	9	6	1	1	21	29	5	217	94	65	475			
	Totals	42						55						376		475
	Σ A Mechanism	266														
	Σ B Mechanism	133														
	Σ C Mechanism	76														

A: Hydraulic mechanism, which may include spring

B: Pneumatic mechanism, which may include spring

C: Spring operated mechanism

Table 2.9.2.4 : Number of minor failures (mf) concerning the population of all the countries for each rated voltage and for each category for which collection of data applies

Voltage (kV)	Circuit-breaker placed in service	Location Indoors						Location Outdoors						Sub Totals	
		Metal enclosed			Non metal enclosed			Metal enclosed			Non metal enclosed				
		Type of operating mechanism			Type of operating mechanism			Type of operating mechanism			Type of operating mechanism				
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
63 ≤ V < 100	1.1.78 - 1.1.83	3	4	3	1	3	0	15	25	7	28	7	2	98	
	After 1.1.83	34	3	1	2	5	0	26	11	13	321	20	8	444	
100 ≤ V < 200	1.1.78 - 1.1.83	61	3	1	3	0	0	32	10	0	219	67	21	417	
	After 1.1.83	46	3	2	0	1	1	21	22	4	426	95	80	701	
200 ≤ V < 300	1.1.78 - 1.1.83	4	0	0	1	0	0	5	13	0	240	27	1	291	
	After 1.1.83	7	0	0	0	0	0	14	21	1	357	40	31	471	
300 ≤ V < 500	1.1.78 - 1.1.83	35	1	0	0	0	0	31	3	0	218	12	0	300	
	After 1.1.83	20	6	0	1	0	0	41	18	0	290	39	55	470	
500 ≤ V < 700	1.1.78 - 1.1.83	0	0	0	0	0	0	2	1	0	23	0	0	26	
	After 1.1.83	80	0	0	0	0	0	5	4	0	26	14	0	129	
700 ≤ V	1.1.78 - 1.1.83	0	0	0	0	0	0	0	0	0	0	0	0	0	
	After 1.1.83	0	0	0	0	1	0	0	0	0	4	6	0	11	
	Subtotals	290	20	7	8	10	1	192	128	25	2152	327	198	3358	
	Totals	317						345						2677	
	Σ A Mechanism	2642													
	Σ B Mechanism	485													
	Σ C Mechanism	231													

A: Hydraulic mechanism, which may include spring

B: Pneumatic mechanism, which may include spring

C: Spring operated mechanism

Table 2.9.2.5 : Failure rates evaluated for different sets of circuit-breakers and associated failures

Circuit-breaker characteristic	Circuit-breaker population		Major failure rate		Minor failure rate	
	Sample size (cb-years)	Sample size (cb-years)	Failures per 100 cb-years	Failures per 100 cb-years	Failures per 100 cb-years	Failures per 100 cb-years
	All countries	All countries minus two extremes 1)	All countries	All countries minus two extremes 1)	All countries	All countries minus two extremes 1)
All breakers	70708	45907	0.67	1.00	4.75	6.90
Metal enclosed	30400	7410	0.32	1.04	2.18	6.44
Non metal enclosed	40308	38497	0.94	0.98	6.69	6.99
Metal enclosed indoor installed cb	8026	4935	0.52	0.73	3.95	6.06
Metal enclosed outdoor installed cb	22374	2475	0.25	1.66	1.54	7.19
Non metal enclosed indoor installed cb	2474	1399	0.08	0.14	0.77	1.29
Non metal enclosed outdoor installed cb	37834	37098	1.00	1.01	7.08	7.20
Metal enclosed installed before 1.1.83	10768	2668	0.28	0.79	2.41	7.01
Metal enclosed installed after 1.1.83	19632	4742	0.34	1.18	2.05	6.12
Non metal encl. installed before 1.1.83	10389	9194	0.86	0.98	8.40	9.47
Non metal encl. installed after 1.1.83	29919	29303	0.97	0.98	6.09	6.21
Metal enclosed with hydraulic mechanism	10258	4378	0.48	0.96	4.70	9.23
Metal enclosed with pneumatic mechanism	13138	1850	0.29	1.51	1.13	3.46
Metal enclosed with spring mechanism	7004	1182	0.16	0.59	0.46	0.76
Non metal enclosed with hydr. mechanism	26124	26044	0.83	0.84	8.27	8.29
Non metal enclosed with pneum. mechanism	8120	6708	1.17	1.42	4.15	5.00
Non metal enclosed with spring mechanism	6064	5745	1.07	1.13	3.28	3.39
Metal enclosed rated below 100 kV	16186	2)	0.07	2)	0.90	2)
Metal enclosed rated 100 kV & above	14214	2)	0.61	2)	3.64	2)
Non metal enclosed rated below 100 kV	8169	2)	0.69	2)	4.86	2)
Non metal enclosed rated 100 kV & above	32139	2)	1.00	2)	7.15	2)

1) All countries excluded those having the two extreme circuit-breaker populations (lowest and highest)

2) Not evaluated

cb = circuit-breaker

2.9.3 History of the circuit breaker

For the history of the circuit-breakers in general, up to the moment when a failure occurred, refer to subchapter 2.10.1 where some tables give more detailed information.

In Table 2.9.3.1 only information is given about the condition of the circuit-breaker when a failure or defect was discovered.

Table 2.9.3.1 : Condition of the circuit-breaker when the failure or defect was discovered

	Second Enquiry				First Enquiry	
	Major failures		Minor failures		Major failures	Minor failures
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Percentage (%)
In service or available for service	91.6	434	85.1	2856	91.2	69.1
During maintenance	6.1	29	13.7	461	4.7	25.1
Other cases	2.3	11	1.2	39	4.1	5.8
Total number of received answers		474		3356		
		1)		2)		

1) Equal to 99.8% of MF of all the countries

2) Equal to 99.9% of mf of all the countries

MF = major failure

mf = minor failure

2.9.4 Identification of the sub-assembly or component responsible for the failure or defect

Information about the identification of the sub-assembly responsible for the failures or defects is given

in Table 2.9.4.1 for the major failures and in Table 2.9.4.2 in the case of the minor failures.

Both tables represent the data for all voltage classes i.e. the data of the whole population.

Table 2.9.4.1 : Identification of the sub-assembly or component responsible for the major failure

	Percentage (%)	Number of answers
1. Component at service voltage:		
-Making and breaking units	14.0	66
-Auxiliary interrupters and resistors	1.3	6
-Main insulation to earth	5.7	27
2. Electrical control and auxiliary circuits:		
-Tripping and closing circuits	10.0	47
-Auxiliary switches and associated drives	7.4	35
-Contactors, relays, heaters, thermostats, fuses and other switches, etc.	7.6	36
-Gas density supervision	4.0	19
3. Operating mechanism:		
-Compressors, motors, pumps, pipework fittings	13.6	64
-Energy storage (accumulator, spring)	7.6	36
-Control elements (non electrical)	9.3	44
-Actuator and damping device	8.9	42
-Mechanical transmission	3.8	18
4. Others	6.8	32
Total number of received answers		472 1)

1) Equal to 99.4% of MF of all the countries

MF = major failure

Table 2.9.4.2 : Identification of the sub-assembly or component responsible for the minor failure

	Percentage (%)	Number of answers
1. Component at service voltage:		
-Making and breaking units	9.4	310
-Auxiliary interrupters and resistors	0.6	20
-Main insulation to earth	20.9	689
2. Electrical control and auxiliary circuits:		
-Tripping and closing circuits	1.5	49
-Auxiliary switches and associated drives	2.1	69
-Contactors, relays, heaters, thermostats, fuses and other switches, etc.	5.4	178
-Gas density supervision	10.7	354
3. Operating mechanism:		
-Compressors, motors, pumps, pipework fittings	18.7	615
-Energy storage (accumulator, spring)	7.2	238
-Control elements (non electrical)	11.6	383
-Actuator and damping device	5.1	168
-Mechanical transmission	1.4	45
4. Others	5.4	178
Total number of received answers		3296 1)

1) Equal to 98.2% of mf of all the countries

mf = minor failure

2.9.5 Stresses presumed contributing to the failure or defect

Table 2.9.5.1 shows the presumed influence of the ambient temperature on the occurrence of the failure or the defect.

Table 2.9.5.2 specifies the impact on the failure event with respect to different environmental conditions.

For more detailed information about the influence of temperature stresses to the breakers and the breaker failures refer to chapter 10 of this brochure.

Table 2.9.5.1 : Stress presumed contributing to the failure / defect : Ambient temperature

	Major failures		Minor failures	
	(%)	Number of answers	(%)	Number of answers
No contribution	95.7	455	98.1	3296
Contribution	4.3	20	1.9	62

Table 2.9.5.2 : Stress presumed contributing to the failure or defect: Environmental condition

	Major failures		Minor failures	
	(%)	Number of answers	(%)	Number of answers
No contribution	91.0	424	94.9	3132
Strong wind	0.6	3	0.1	2
Rain	0.2	1	1.2	39
Sudden variation in temperature	2.4	11	0.8	28
Snow, ice or hoar-frost	0.6	3	0.2	8
Corrosive atmosphere	0.2	1	0.5	16
Fog or high humidity	0.9	4	1.6	53
Pollution including dust	0.2	1	0.3	10
Lightning	2.8	13	0.1	2
Others	1.1	5	0.3	9
Total number of received answers		466		3299
		1)		2)

1) Equal to 98.1% of MF of all the countries

2) Equal to 98.2% of mf of all the countries

MF = major failure

mf = minor failure

2.9.6 Characteristics of failure or defect

The classification of the failures, distinguishing between major failures and minor failures, is given in Tables 2.9.6.1 and 2.9.6.2.

In difference to the second enquiry, for the first enquiry the failure modes (Failure characteristics) *Locking in open or closed position* and the complete list of the minor failure modes has not been specified.

Table 2.9.6.1 : Characteristics of the major failures

	All voltages		
	Second Enquiry		First Enquiry
	Percentage (%)	Number of answers	Percentage (%)
Does not close on command	24.6	116	33.7
Does not open on command	8.3	39	14.1
Closes without command	1.1	5	1.7
Opens without command	7.0	33	5.2
Does not make the current	1.7	8	1.6
Does not break the current	3.0	14	1.9
Fails to carry the current	1.5	7	2.5
Breakdown to earth	3.2	15	2.6
Breakdown between poles	1.5	7	0.5
Breakdown across open pole (internal)	3.6	17	4.0
Breakdown across open pole (external)	1.5	7	1.2
Locking in open or closed position	28.4	134	1)
Others	14.6	69	31.0
Total number of received answers		471 2)	773

1) Not specified

MF = major failure

2) Equal to 99.2% of MF of all the countries

Table 2.9.6.2 : Characteristics of the minor failures

	All voltages		
	Second Enquiry		First Enquiry
	Percentage (%)	Number of answers	Percentage (%)
Air or hydraulic oil leakage in operating mechanism	29.9	999	1)
Small SF6 leakage due to corrosion	15.8	528	1)
Small SF6 leakage due to other causes	23.0	769	1)
Change in functional characteristics	16.2	543	1)
Others	14.7	493	1)
Total number of received answers		3332 2)	

1) Not specified

mf = minor failure

2) Equal to 99.2% of mf of all countries

2.9.7 Origin and cause of the failures or defects

The origin of the failures or defects is specified in Table 2.9.7.1 for the major failures and in Table 2.9.7.2 for the minor failures.

Tables 2.9.7.3 and 2.9.7.4 give the causes of the failures or defects. For both, the origin and the causes as far as possible, comparison to the first enquiry is made. Note that for the first enquiry evaluation of failure causes has been made together for *Design* and *Manufacture*.

Table 2.9.7.1 : Origin of major failures

	All voltages						
	Second Enquiry						First Enquiry
	Placed in service 1.1.78-1.1.83		Placed in service After 1.1.83		All period		
	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)
Mechanical in operating mechanism (earthed)	30.4	35	48.6	168	44.0	203	1)
Mechanical in other parts of circuit-breaker	14.8	17	9.0	31	10.4	48	70.3
Electrical (main circuit)	12.2	14	14.5	50	13.9	64	10.6
Electrical (auxiliary and control circuit)	29.6	34	22.8	79	24.5	113	19.1
Tightness of SF6-gas system	13.0	15	5.2	18	7.2	33	1)
Total number of received answers		115		346		461	
		2)		3)		4)	

1) Not specified

2) Equal to 96.6% of MF of all the countries

3) Equal to 97.2% of MF of all the countries

4) Equal to 97.1% of MF of all the countries

MF = major failure

Table 2.9.7.2 : Origin of minor failures

	All voltages						
	Second Enquiry						First Enquiry
	Placed in service 1.1.78-1.1.83		Placed in service After 1.1.83		All period		
	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)
Mechanical in operating mechanism (earthed)	32.0	350	43.2	925	39.4	1275	1)
Mechanical in other parts of circuit-breaker	9.6	105	10.0	214	9.9	319	85.6
Electrical (main circuit)	1.0	11	0.8	18	0.9	29	2.7
Electrical (auxiliary and control circuit)	9.6	105	10.5	225	10.2	330	11.7
Tightness of SF6-gas system	47.8	522	35.4	758	39.6	1280	1)
Total number of received answers		1093		2140		3233	
		2)		3)		4)	

1) Not specified

2) Equal to 96.6% of mf of all the countries

3) Equal to 96.1% of mf of all the countries

4) Equal to 96.3% of mf of all the countries

mf = minor failure

Table 2.9.7.3 : Cause of major failures

	All voltages						
	Second Enquiry						First Enquiry
	Placed in service 1.1.78-1.1.83		Placed in service After 1.1.83		All period		
	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)
Design	17.2	20	28.2	98	25.4	118	\ 45.3
Manufacture	26.7	31	29.3	102	28.7	133	
Inadequate instruction (erection, operation, maintenance)	0.9	1	1.1	4	1.1	5	0.7
Incorrect erection	5.2	6	9.2	32	8.2	38	9.3
Incorrect operation	7.8	9	5.5	19	6.0	28	1.2
Incorrect maintenance	7.8	9	1.1	4	2.8	13	8.1
Stresses beyond those specified	3.4	4	3.4	12	3.4	16	4.8
Other external causes	4.3	5	5.7	20	5.4	25	2.3
Other	26.7	31	16.4	57	19.0	88	28.3
Total number of received answers		116		348		464	
		1)		2)		3)	

1) Equal to 97.5% of MF of all the countries

MF = major failure

2) Equal to 97.8% of MF of all the countries

3) Equal to 97.7% of MF of all the countries

Table 2.9.7.4 : Cause of minor failures

	All voltages						
	Second Enquiry						First Enquiry
	Placed in service 1.1.78-1.1.83		Placed in service After 1.1.83		All period		
	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)
Design	33.6	373	20.2	442	24.7	815	\ 52.5
Manufacture	30.9	343	43.3	945	39.1	1288	
Inadequate instruction (erection, operation, maintenance)	1.2	13	2.0	44	1.7	57	0.3
Incorrect erection	2.5	28	9.5	207	7.1	235	10.7
Incorrect operation	3.9	43	4.8	104	4.5	147	0.2
Incorrect maintenance	3.2	35	2.3	51	2.6	86	4.5
Stresses beyond those specified	2.3	25	1.6	34	1.8	59	0.7
Other external causes	9.3	103	5.2	113	6.6	216	1.7
Other	13.3	148	11.1	243	11.9	391	29.4
Total number of received answers		1111		2183		3294	
		1)		2)		3)	

1) Equal to 98.1% of mf of all the countries

mf = minor failure

2) Equal to 98.1% of mf of all the countries

3) Equal to 98.1% of mf of all the countries

2.9.8 Breakdowns, fire and/or explosions

Obviously, failure modes of very special interest are electrical breakdown, fire and explosion. These failures are definitely amongst the most severe ones because of their heavy impact on equipment and sometimes even on human beings. On the other hand these failure rates are extremely low, which proof Tables 2.9.8.1 to Tables 2.9.8.4.

The overall breakdown failure rate is 0.065 breakdowns per 100 circuit-breaker-years which results in a mean time between failure of 1537 years. The fire and/or explosion rate for the complete population is 0.044 failures per 100 circuit-breaker-years, resulting

in a mean time between failure of 2281 years.

Table 2.9.8.1 shows the breakdown figures for all the collected data. On the basis of this table the electrical breakdown rates are indicated in Table 2.9.8.2.

Tables 2.9.8.3 and 2.9.8.4 reveal information about failure modes and failure causes related to fire and/or explosion of the circuit-breaker.

Table 2.9.8.1 : Number of major failures characterized by an electrical breakdown, concerning the population of all the countries

Voltage (kV)	Location Indoors		Location Outdoors		Total Sub-Total
	Metal enclosed	Non metal enclosed	Metal enclosed	Non metal enclosed	
All Voltages	6	1	13	26	46
63 ≤ V < 100	0	0	2	10	12
100 ≤ V < 200	0	0	0	5	5
200 ≤ V < 300	0	1	5	3	9
300 ≤ V < 500	3	0	6	5	14
500 ≤ V < 700	3	0	0	3	6
700 ≤ V	0	0	0	0	0

Table 2.9.8.2 : Electrical breakdown failure rates

Voltage (kV)	Location Indoors				Location Outdoors				Total population	
	Metal enclosed		Non metal enclosed		Metal enclosed		Non metal enclosed		Sample size (cb-years)	Failures per 100 cb-years
	Sample size (cb-years)	Failures per 100 cb-years	Sample size (cb-years)	Failures per 100 cb-years	Sample size (cb-years)	Failures per 100 cb-years	Sample size (cb-years)	Failures per 100 cb-years		
All voltages	8026	0.075	2474	0.040	22374	0.058	37834	0.069	70708	0.065
63 ≤ V < 100	2781	0.000	1485	0.000	13405	0.015	6684	0.150	24355	0.049
100 ≤ V < 200	3474	0.000	472	0.000	3952	0.000	15622	0.032	23520	0.021
200 ≤ V < 300	264	0.000	135	0.741	1186	0.422	9348	0.032	10933	0.082
300 ≤ V < 500	1274	0.235	373	0.000	2825	0.212	5445	0.092	9917	0.141
500 ≤ V < 700	233	1.288	9	0.000	1003	0.000	650	0.462	1895	0.317
700 ≤ V	0	0.000	0	0.000	3	0.000	85	0.000	88	0.000

cb = circuit-breaker

Table 2.9.8.3 : Modes (characteristics) of the major failures having fire and/or explosion of the circuit-breaker as a consequence (Number of failures)

Voltage (kV)	Characteristics of failures												
	Does not close on command	Does not open on command	Closes without command	Opens without command	Does not make the current	Does not break the current	Falls to carry the current	Breakdown to earth	Breakdown between poles	Breakdown across open pole (int)	Breakdown across open pole (ext)	Locking in open or closed position	Other
All voltages	0	1	0	0	1	1	1	2	3	12	5	0	4
63 ≤ V < 100	0	1	0	0	0	0	0	1	0	6	3	0	2
100 ≤ V < 200	0	0	0	0	0	1	1	0	1	3	0	0	1
200 ≤ V < 300	0	0	0	0	0	0	0	1	0	1	0	0	0
300 ≤ V < 500	0	0	0	0	0	0	0	0	2	0	1	0	0
500 ≤ V < 700	0	0	0	0	1	0	0	0	0	2	1	0	1
700 ≤ V	0	0	0	0	0	0	0	0	0	0	0	0	0

Total number of answers: 30

Table 2.9.8.4 : Causes of the major failures having fire and/or explosion of the circuit-breaker as a consequence (Number of failures)

Voltage (kV)	Failure causes								
	Design	Manufacture	Inadequate instructions for erection, operation and maintenance	Incorrect erection	Incorrect operation	Incorrect maintenance	Stresses beyond those specified	Other external causes	Other
All voltages	5	6	0	1	1	0	1	4	13
63 ≤ V < 100	0	1	0	0	0	0	0	2	10
100 ≤ V < 200	1	3	0	0	1	0	0	0	2
200 ≤ V < 300	1	0	0	0	0	0	0	1	0
300 ≤ V < 500	0	1	0	0	0	0	1	1	1
500 ≤ V < 700	3	1	0	1	0	0	0	0	0
700 ≤ V	0	0	0	0	0	0	0	0	0

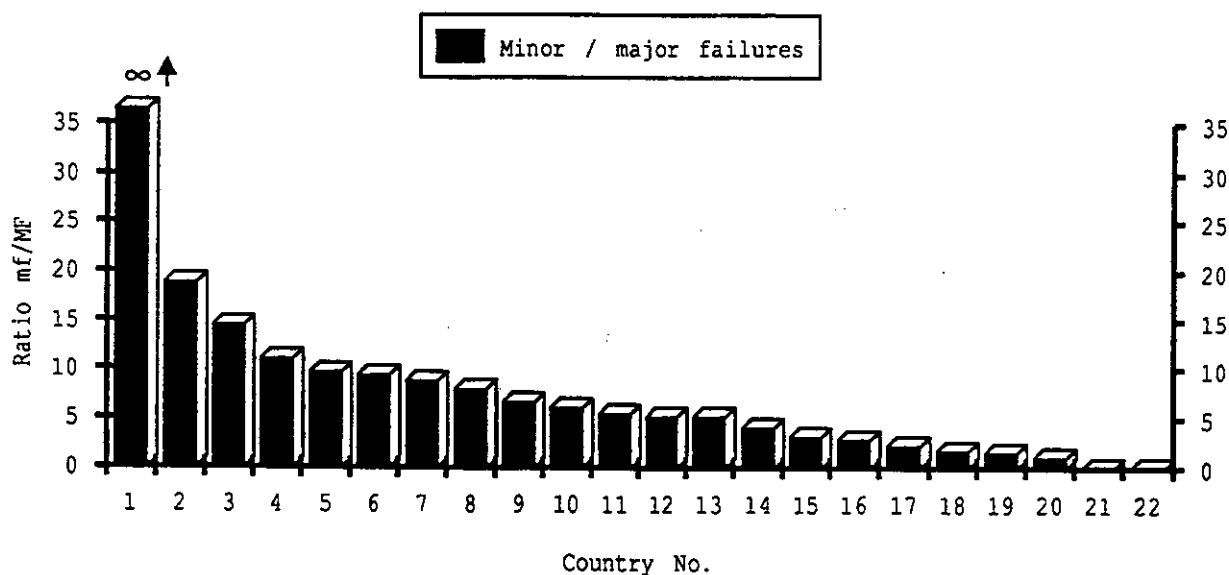
Total number of answers: 31

2.10 Other tables and evaluations

2.10.1 General and history of the circuit-breaker

Fig. 2.10.1.1 gives the interesting information about the ratio of minor failures / major failures for the different countries. The numbering of the countries is not the same as for Figures 2.9.1.1 and 2.9.1.2. Fig. 2.10.1.1 contains three particular cases: Country No.1, No.21 and No.22. While country No.22 reported no failures at all, country No.21 reported only some major failures. Country No.1 reported no major failures but some minor failures, which causes the ratio mf/MF to be infinite.

Fig. 2.10.1.1 : Ratio of mf/MF per country
Years 1988-1991



Tables 2.10.1.1 to 2.10.1.4 give information about the estimated number of operating cycles since commissioning or last overhaul until a failure occurred.

2.10.2 Cross correlations

The Tables 2.10.2.1 to 2.10.2.10 gives figures and information about correlation between different items.

These correlations concern the components responsible for failures, the failure causes, the failure modes (characteristics) and the origin of failures.

All these correlation tables allow very interesting evaluations on various items. For such studies see the special chapters (3-10) of this Technical Brochure.

Table 2.10.1.1 : Estimated average number of operating cycles since commissioning until a major failure occurred

Statistical Parameter	Voltage Classes						All
	63≤V<100	100≤V<200	200≤V<300	300≤V<500	500≤V<700	700≤V	
Average	489	356	471	646	504	125	471
10% Percentile	13	22	30	76	60	8	30
25% Percentile	75	58	143	110	96	8	80
50% Percentile	198	158	250	245	250	50	218
75% Percentile	501	320	507	460	400	200	400
90% Percentile	1800	750	923	1252	1649	240	1102
95% Percentile	2065	1355	1169	1900	1881	240	1800
Maximum	3140	5168	5584	11579	4008	240	11579
Number of failures	45	114	61	71	32	4	327

Table 2.10.1.2 : Estimated average number of operating cycles since commissioning until a minor failure occurred

Statistical Parameter	Voltage Classes						
	63≤V<100	100≤V<200	200≤V<300	300≤V<500	500≤V<700	700≤V	All
Average	383	353	441	746	316	170	453
10% Percentile	22	21	42	30	35	120	25
25% Percentile	75	75	100	85	64	120	80
50% Percentile	163	180	200	196	179	120	183
75% Percentile	314	336	431	409	450	220	379
90% Percentile	868	720	1241	886	708	220	840
95% Percentile	1225	1182	1538	1800	909	220	1408
Maximum	7271	8800	4267	14682	4509	220	14682
Number of failures	299	702	311	395	147	2	1856

Table 2.10.1.3 : Estimated average number of operating cycles since last overhaul until a major failure occurred

Statistical Parameters	Voltage Classes						
	63≤V<100	100≤V<200	200≤V<300	300≤V<500	500≤V<700	700≤V	All
Average	112	218	97	214	209	20	178
10% Percentile	7	5	4	2	3	6	3
25% Percentile	19	20	11	12	9	6	19
50% Percentile	87	50	48	32	68	6	50
75% Percentile	121	130	87	146	197	34	146
90% Percentile	341	380	263	344	400	34	346
95% Percentile	363	1265	476	1252	437	34	780
Maximum	363	4503	780	2368	1800	34	4503
Number of failures	17	57	35	40	20	2	171

Table 2.10.1.4 : Estimated average number of operating cycles since last overhaul until a minor failure occurred

Statistical Parameters	Voltage Classes						
	63≤V<100	100≤V<200	200≤V<300	300≤V<500	500≤V<700	700≤V	All
Average	150	147	222	193	135	10	171
10% Percentile	0	2	0	0	0	10	0
25% Percentile	15	11	11	13	6	10	10
50% Percentile	49	40	35	36	18	10	36
75% Percentile	123	146	168	130	90	10	132
90% Percentile	279	490	307	403	258	10	386
95% Percentile	628	687	747	636	498	10	687
Maximum	3346	2023	7272	13983	4982	10	13983
Number of failures	128	328	207	208	116	1	988

Table 2.10.2.1 : Correlation concerning the origin of failure and the component responsible for the major failure

	Origin of major failures												Total number of answers
	Mechanical in operating mechanism (earthed)		Mechanical in other parts of the circuit-breaker		Electrical (main circuit)		Electrical (auxiliary and control circuit)		Tightness of SF6 gas system		Number of answers		
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers			
1. Component at service voltage:													
-Making and breaking units	1.0	2	31.3	15	65.5	42	0.9	1	18.8	6	66		
-Auxiliary interrupters and resistors	0.5	1	2.1	1	3.1	2	0.9	1	0.0	0	5		
-Main insulation to earth	1.0	2	8.3	4	12.5	8	0.0	0	34.4	11	25		
2. Electrical control and aux.circuits:													
-Tripping and closing circuits	3.5	7	0.0	0	3.1	2	32.7	37	0.0	0	46		
-Aux. switches and associated drives	4.5	9	4.2	2	1.6	1	20.4	23	0.0	0	35		
-Contactors, relays, heaters, thermostats etc	1.0	2	2.1	1	0.0	0	29.2	33	0.0	0	36		
-Gas density supervision	1.5	3	10.4	5	0.0	0	5.3	6	15.6	5	19		
3. Operating mechanism:													
-Compressors, motors, pumps, pipework fitting	20.8	42	18.8	9	0.0	0	8.0	9	3.1	1	61		
-Energy storage (accumulator, springs)	17.3	35	0.0	0	0.0	0	0.0	0	3.1	1	36		
-Control elements (non electrical)	18.8	38	6.3	3	0.0	0	2.7	3	0.0	0	44		
-Actuators and damping device	19.8	40	4.2	2	0.0	0	0.0	0	0.0	0	42		
-Mechanical transmission	5.9	12	6.3	3	0.0	0	0.0	0	9.4	3	18		
4. Others	4.5	9	6.3	3	14.1	9	0.0	0	15.6	5	26		
Total number of received answers		202		48		64		113		32	459		

Table 2.10.2.2 : Correlation concerning the origin of failure and the component responsible for the minor failure

	Origin of minor failures										Total number of answers	
	Mechanical in operating mechanism (earthed)		Mechanical in other parts of the circuit-breaker		Electrical (main circuit)		Electrical (auxiliary and control circuit)		Tightness of SF6 gas system			
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers		
1. Component at service voltage:												
-Making and breaking units	0.6	7	7.9	25	75.9	22	0.9	3	19.7	244	301	
-Auxiliary interrupters and resistors	0.2	2	3.1	10	6.9	2	0.0	0	0.4	5	19	
-Main insulation to earth	0.4	5	6.3	20	3.4	1	0.6	2	53.2	658	686	
2. Electrical control and aux. circuits:												
-Tripping and closing circuits	1.0	13	0.9	3	6.9	2	8.2	27	0.2	2	47	
-Aux. switches and associated drives	0.6	7	2.5	8	0.0	0	15.8	52	0.1	1	68	
-Contactors, relays, heaters, thermostats etc	0.5	6	1.9	6	0.0	0	45.5	150	0.2	3	165	
-Gas density supervision	3.4	43	18.2	58	0.0	0	18.5	61	14.2	176	338	
3. Operating mechanism:												
-Compressors, motors, pumps, pipework fitting	34.9	442	26.1	83	3.4	1	3.9	13	2.8	34	573	
-Energy storage (accumulator, springs)	15.2	192	11.0	35	0.0	0	0.3	1	0.2	3	231	
-Control elements (non electrical)	26.3	333	6.3	20	0.0	0	4.5	15	0.6	7	375	
-Actuators and damping device	11.5	145	4.1	13	0.0	0	0.3	1	0.4	5	164	
-Mechanical transmission	1.6	20	3.1	10	0.0	0	0.0	0	1.1	13	43	
4. Others	4.0	51	8.5	27	3.4	1	1.5	5	6.9	85	169	
Total number of received answers		1266		318		29		330		1236	3179	
		1)		2)		3)		4)		5)		

1) Equal to 99.3% of mf of all the countries

2) Equal to 99.7% of mf of all the countries

3) Equal to 100% of mf of all the countries

4) Equal to 100% of mf of all the countries

5) Equal to 96.6% of mf of all the countries

mf = minor failure

Table 2.10.2.3 : Correlation concerning the components responsible for the major failures and its causes

	Major failure causes														Total number of answers				
	Design		Manufacture		Inadequate instruction for erection		Incorrect erection		Incorrect operation		Incorrect maintenance		Stresses beyond those specified			Other external causes		Other	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers		Percentage (%)	Number of answers	Percentage (%)	Number of answers
1. Component at service voltage:																			
-Making and breaking units	12.8	15	11.3	15	0.0	0	18.4	7	14.3	4	7.7	1	46.7	7	24.0	6	10.2	9	64
-Auxiliary interrupters and resistors	0.9	1	1.5	2	0.0	0	2.6	1	0.0	0	0.0	0	0.0	0	4.0	1	1.1	1	6
-Main insulation to earth	5.1	6	4.5	6	0.0	0	2.6	1	0.0	0	15.4	2	6.7	1	8.0	2	8.0	7	25
2. Electrical control and aux. circuits:																			
-Tripping and closing circuits	8.5	10	9.0	12	20.0	1	10.5	4	7.1	2	30.8	4	0.0	0	8.0	2	13.6	12	47
-Aux. switches and associated drives	1.7	2	7.5	10	0.0	0	15.8	6	25.0	7	15.4	2	0.0	0	0.0	0	9.1	8	35
-Contactors, relays, heaters, thermostats etc	6.0	7	10.5	14	0.0	0	2.6	1	7.1	2	0.0	0	6.7	1	28.0	7	4.5	4	36
-Gas density supervision	0.9	1	7.5	10	0.0	0	10.5	4	0.0	0	7.7	1	0.0	0	0.0	0	1.1	1	17
3. Operating mechanism:																			
-Compressors, motors, pumps, pipework fitting	16.2	19	16.5	22	0.0	0	5.3	2	3.6	1	15.4	2	20.0	3	12.0	3	10.2	9	61
-Energy storage (accumulator, springs)	15.4	18	2.3	3	0.0	0	5.3	2	17.9	5	0.0	0	20.0	3	0.0	0	5.7	5	36
-Control elements (non electrical)	5.1	6	9.8	13	40.0	2	10.5	4	10.7	3	7.7	1	0.0	0	4.0	1	14.8	13	43
-Actuators and damping device	16.2	19	5.3	7	40.0	2	7.9	3	10.7	3	0.0	0	0.0	0	4.0	1	8.0	7	42
-Mechanical transmission	5.1	6	7.5	10	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	2.3	2	18
4. Others	6.0	7	6.8	9	0.0	0	7.9	3	3.6	1	0.0	0	0.0	0	8.0	2	11.4	10	32
Total number of received answers		117		133		5		38		28		13		15		25		88	462

Table 2.10.2.4 : Correlation concerning the components responsible for the minor failures and its causes

	Minor failure causes														Total number of answers				
	Design		Manufacture		Inadequate instruction for erection		Incorrect erection		Incorrect operation		Incorrect maintenance		Stresses beyond those specified			Other external causes		Other	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers		Percentage (%)	Number of answers	Percentage (%)	Number of answers
1. Component at service voltage:																			
-Making and breaking units	13.7	110	7.6	96	5.3	3	3.9	9	0.0	0	4.7	4	18.6	11	7.0	15	15.6	60	308
-Auxiliary interrupters and resistors	0.9	7	0.5	6	0.0	0	0.0	0	0.0	0	0.0	0	1.7	1	1.4	3	0.5	2	19
-Main insulation to earth	34.5	277	21.0	265	3.5	2	12.1	28	9.5	14	12.8	11	0.0	0	14.0	30	14.8	57	684
2. Electrical control and aux. circuits:																			
-Tripping and closing circuits	0.6	5	1.0	13	0.0	0	3.0	7	4.1	6	2.3	2	8.5	5	3.3	7	0.8	3	48
-Aux. switches and associated drives	1.2	10	1.3	17	1.8	1	1.3	3	7.5	11	1.2	1	1.7	1	5.1	11	3.4	13	68
-Contactors, relays, heaters, thermostats etc	6.2	50	4.8	60	0.0	0	1.3	3	7.5	11	1.2	1	3.4	2	8.4	18	8.1	31	176
-Gas density supervision	4.9	39	13.4	169	1.8	1	9.1	21	40.1	59	4.7	4	6.8	4	12.1	26	5.5	21	344
3. Operating mechanism:																			
-Compressors, motors, pumps, pipework fitting	15.7	126	16.9	214	28.1	16	36.8	85	4.8	7	27.9	24	18.6	11	22.3	48	17.7	68	599
-Energy storage (accumulator, springs)	8.9	71	7.6	96	1.8	1	3.5	8	0.7	1	5.8	5	5.1	3	5.6	12	9.6	37	234
-Control elements (non electrical)	5.2	42	13.4	169	28.1	16	10.8	25	18.4	27	31.4	27	3.4	2	7.9	17	14.1	54	379
-Actuators and damping device	2.4	19	5.5	69	24.6	14	3.9	9	6.1	9	0.0	0	23.7	14	5.6	12	5.7	22	168
-Mechanical transmission	1.5	12	1.0	12	3.5	2	1.7	4	1.4	2	4.7	4	3.4	2	1.4	3	1.0	4	45
4. Others	4.2	34	6.1	77	1.8	1	12.6	29	0.0	0	3.5	3	5.1	3	6.0	13	3.1	12	172
Total number of received answers		802		1263		57		231		147		86		59		215		384	3244
		1)		2)		6)		3)		6)		6)		6)		4)		5)	5)

mf = minor failure

1) Equal to 98.4% of mf of all the countries

2) Equal to 98.1% of mf of all the countries

3) Equal to 98.3% of mf of all the countries

4) Equal to 99.5% of mf of all the countries

5) Equal to 98.2% of mf of all the countries

6) Equal to 100% of mf of all the countries

Table 2.10.2.5 : Correlation concerning the components responsible for the major failures and the characteristics (mode) of the major failure

		Characteristics of major failures																		Total number of received answers							
		Does not close on command		Does not open on command		Closes without command		Opens without command		Does not make the current		Does not break the current		Fails to carry the current		Breakdown between poles		Breakdown acf. open pole (int)				Breakdown acf. open pole (ext)		Locking closed or open pos.		Others	
Percentage	Number of answers	Percentage	Number of answers	Percentage	Number of answers	Percentage	Number of answers	Percentage	Number of answers	Percentage	Number of answers	Percentage	Number of answers	Percentage	Number of answers	Percentage	Number of answers	Percentage	Number of answers	Percentage	Number of answers	Percentage	Number of answers	Percentage	Number of answers		
1. Component at service voltage:																											
-Making and breaking units																											
0.9	1	5.1	2	0.0	0	3.0	1	12.5	1	78.6	11	42.9	3	53.3	8	100	7	58.8	10	57.1	4	6.0	8	14.9	10	66	
-Auxiliary interrupters and resistors																											
0.0	0	0.0	0	0.0	0	3.0	1	12.5	1	0.0	0	0.0	0	0.0	0	0.0	0	11.8	2	0.0	0	0.8	1	1.5	1	6	
-Main insulation to earth																											
0.0	0	2.6	1	0.0	0	12.1	4	12.5	1	7.1	1	14.3	1	40.0	6	0.0	0	0.0	0	28.6	2	4.5	6	4.5	3	25	
2. Electrical control and aux. circuits:																											
-Tripping and closing circuits																											
19.0	22	33.3	13	20.0	1	21.2	7	0.0	0	0.0	0	14.3	1	0.0	0	0.0	0	0.0	0	0.0	0	2.3	3	0.0	0	47	
-Aux. switches and associated drives																											
13.8	16	12.8	5	0.0	0	3.0	1	25.0	2	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	4.5	6	7.5	5	35	
-Contactors, relays, heaters, thermostats etc																											
20.7	24	5.1	2	0.0	0	0.0	0	0.0	0	0.0	0	28.6	2	0.0	0	0.0	0	0.0	0	0.0	0	6.0	8	0.0	0	36	
-Gas density supervision																											
3.4	4	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	10.5	14	0.0	0	18	
3. Operating mechanism:																											
-Compressors, motors, pumps, pipework fitting																											
7.8	9	2.6	1	40.0	2	9.1	3	37.5	3	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	14.3	1	21.1	28	23.9	16	63	
-Energy storage (accumulator, springs)																											
6.0	7	7.7	3	0.0	0	9.1	3	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	5.9	1	0.0	0	14.3	19	4.5	3	36	
-Control elements (non electrical)																											
12.1	14	20.5	8	20.0	1	9.1	3	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	8.3	11	10.4	7	44	
-Actuators and damping device																											
9.5	11	5.1	2	20.0	1	15.2	5	0.0	0	7.1	1	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	13.5	18	6.0	4	42	
-Mechanical transmission																											
5.2	6	5.1	2	0.0	0	9.1	3	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	5.3	7	0.0	0	18	
1.7	2	0.0	0	0.0	0	6.1	2	0.0	0	7.1	1	0.0	0	6.7	1	0.0	0	23.5	4	0.0	0	3.0	4	26.9	18	32	
4. Others																											
Total number of received answers																											
116	39	5	33	8	14	7	15	7	17	7	133	67	468														

Table 2.10.2.6 : Correlation concerning the components responsible for the minor failures and the characteristics (mode) of the minor failure

	Characteristics of minor failures										Total number of answers	
	Air or hydraulic oil leakage in oper. mechanism		Small SF6 leakage due to corrosion		Small SF6 leakage due to other causes		Change in functional characteristics		Others			
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers		
1. Component at service voltage:												
-Making and breaking units	0.8	8	16.1	84	24.1	176	1.7	9	6.4	31	308	
-Auxiliary interrupters and resistors	0.7	7	0.4	2	0.5	4	0.9	5	0.4	2	20	
-Main insulation to earth	0.3	3	74.7	390	35.4	258	1.3	7	6.1	30	688	
2. Electrical control and auxiliary circuits:												
-Tripping and closing circuits	1.1	11	0.2	1	0.1	1	3.7	20	3.1	15	48	
-Auxiliary switches and associated drives	0.4	4	0.0	0	0.1	1	7.2	39	4.7	23	67	
-Contactors, relays, heaters, thermostats etc.	0.1	1	0.2	1	0.3	2	17.0	92	16.0	78	174	
-Gas density supervision	0.2	2	3.1	16	19.3	141	25.5	138	11.1	54	351	
3. Operating mechanism:												
-Compressors, motors, pumps, pipework fitting	40.5	401	0.4	2	5.5	40	12.4	67	20.5	100	610	
-Energy storage (accumulator, springs)	13.0	129	0.0	0	1.0	7	9.2	50	10.2	50	236	
-Control elements (non electrical)	28.1	278	0.0	0	0.8	6	14.4	78	3.9	19	381	
-Actuators and damping device	11.5	114	0.2	1	1.2	9	4.8	26	3.3	16	166	
-Mechanical transmission	0.8	8	0.4	2	2.3	17	0.9	5	2.5	12	44	
4. Others	2.4	24	4.4	23	9.2	67	0.9	5	11.9	58	177	
Total number of received answers		990		522		729		541		488	3270	
		1)		2)		3)		4)		5)		

mf = minor failure

1) Equal to 99.1% of mf of all the countries

2) Equal to 98.9% of mf of all the countries

3) Equal to 94.8% of mf of all the countries

4) Equal to 99.6% of mf of all the countries

5) Equal to 99.0% of mf of all the countries

Table 2.10.2.7 : Correlation concerning the characteristics (mode) of the major failure and its origin

	Origin of major failures												Total number of answers
	Mechanical in operating mechanism (earthed)		Mechanical in other parts of the circuit-breaker		Electrical (main circuit)		Electrical (auxiliary and control circuit)		Tightness of SF6 gas system		Total number of answers		
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers			
Does not close on command	24.6	50	19.1	9	1.6	1	48.7	55	0.0	0	115		
Does not open on command	7.9	16	6.4	3	0.0	0	16.8	19	3.2	1	39		
Closes without command	2.5	5	0.0	0	0.0	0	0.0	0	0.0	0	5		
Opens without command	9.4	19	2.1	1	4.7	3	3.5	4	16.1	5	32		
Does not make the current	1.5	3	2.1	1	1.6	1	1.8	2	3.2	1	8		
Does not break the current	0.5	1	4.3	2	14.1	9	0.0	0	6.5	2	14		
Falls to carry the current	0.0	0	0.0	0	6.3	4	2.7	3	0.0	0	7		
Breakdown to earth	0.0	0	2.1	1	21.9	14	0.0	0	0.0	0	15		
Breakdown between poles	0.0	0	6.4	3	6.3	4	0.0	0	0.0	0	7		
Breakdown across open poles (Internal)	2.5	5	4.3	2	12.5	8	0.9	1	0.0	0	16		
Breakdown across open poles (external)	0.0	0	0.0	0	7.8	5	0.0	0	3.2	1	6		
Locking in open or closed position	34.0	69	38.3	18	1.6	1	23.0	26	58.1	18	132		
Others	17.2	35	14.9	7	21.9	14	2.7	3	9.7	3	62		
Total number of received answers		203		47		64		113		31	458		

i) Equal to 100% of MF of all countries

MF = major failure

Table 2.10.2.8 : Correlation concerning the characteristics (mode) of the minor failure and its origin

	Origin of minor failures										Total number of answers
	Mechanical in operating mechanism (earthed)		Mechanical in other parts of the circuit-breaker		Electrical (main circuit)		Electrical (auxiliary and control circuit)		Tightness of SF6 gas system		
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	
Air or hydr. oil leakage in op. mechanism	66.0	837	34.6	108	13.8	4	0.6	2	0.4	5	956
Small SF6 leakage due to corrosion	0.4	5	0.3	1	0.0	0	0.3	1	40.7	520	527
Small SF6 leakage due to other causes	1.8	23	11.2	35	3.4	1	0.6	2	54.6	698	759
Change in functional characteristics	16.1	204	30.1	94	20.7	6	62.1	200	2.1	27	531
Others	15.7	199	23.7	74	62.1	18	36.3	117	2.2	28	436
Total number of received answers		1268		312		29		322		1278	3209

Table 2.10.2.9 : Correlation concerning the characteristics (mode) of the major failure and its cause

	Major failure causes														Total number of answers				
	Design		Manufacture		Inadequate instruction for erection		Incorrect erection		Incorrect operation		Incorrect maintenance		Stresses beyond those specified			Other external causes		Other	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers		Percentage (%)	Number of answers	Percentage (%)	Number of answers
Does not close on command	23.1	27	33.1	43	20.0	1	26.3	10	17.9	5	23.1	3	0.0	0	24.0	6	23.9	21	116
Does not open on command	3.4	4	5.4	7	20.0	1	10.5	4	14.3	4	23.1	3	18.8	3	4.0	1	13.6	12	39
Closes without command	1.7	2	2.3	3	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	5
Opens without command	7.7	9	6.2	8	0.0	0	13.2	5	7.1	2	7.7	1	0.0	0	4.0	1	8.0	7	33
Does not make the current	1.7	2	1.5	2	0.0	0	2.6	1	0.0	0	0.0	0	0.0	0	0.0	0	3.4	3	8
Does not break the current	4.3	5	2.3	3	0.0	0	0.0	0	7.1	2	0.0	0	6.3	1	8.0	2	1.1	1	14
Fails to carry the current	0.9	1	0.8	1	0.0	0	2.6	1	3.6	1	0.0	0	0.0	0	8.0	2	1.1	1	7
Breakdown to earth	1.7	2	1.5	2	0.0	0	0.0	0	0.0	0	23.1	3	0.0	0	8.0	2	6.8	6	15
Breakdown between poles	1.7	2	2.3	3	0.0	0	0.0	0	0.0	0	0.0	0	6.3	1	4.0	1	0.0	0	7
Breakdown across open pole (internal)	1.7	2	1.5	2	0.0	0	5.3	2	7.1	2	0.0	0	6.3	1	0.0	0	9.1	8	17
Breakdown across open pole (external)	0.9	1	0.8	1	0.0	0	2.6	1	0.0	0	0.0	0	0.0	0	12.0	3	1.1	1	7
Locking in open or closed position	38.5	45	30.0	39	20.0	1	23.7	9	17.9	5	23.1	3	18.8	3	16.0	4	19.3	17	126
Others	12.8	15	12.3	16	40.0	2	13.2	5	25.0	7	0.0	0	43.8	7	12.0	3	12.5	11	66
Total number of received answers		117		130		5		38		28		13		16		25		88	460

1) Equal to 97.7% of MF of all countries

MF = major failure

Table 2.10.2.10 : Correlation concerning the characteristics (mode) of the minor failure and its cause

	Minor failure causes														Total number of answers				
	Design		Manufacture		Inadequate instruction for erection		Incorrect erection		Incorrect operation		Incorrect maintenance		Stresses beyond those specified			Other external causes		Other	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers		Percentage (%)	Number of answers	Percentage (%)	Number of answers
Air or hydr. oil leakage in op. mechanism	20.3	165	28.9	371	74.1	40	46.1	107	17.8	26	50.0	43	49.2	29	33.0	71	31.3	120	972
Small SF6 leakage due to corrosion	43.2	351	11.3	145	1.9	1	0.9	2	0.0	0	2.3	2	0.0	0	8.4	18	1.6	6	525
Small SF6 leakage due to other causes	8.5	69	29.1	373	9.3	5	33.6	78	9.6	14	18.6	16	16.9	10	27.9	60	31.8	122	747
Change in functional characteristics	15.5	126	15.5	199	3.7	2	6.5	15	64.4	94	12.8	11	18.6	11	15.8	34	12.0	46	538
Others	12.4	101	15.1	194	11.1	6	12.9	30	8.2	12	16.3	14	15.3	9	14.9	32	23.4	90	488
Total number of received answers		812		1282		54		232		146		86		59		215		384	3270

2.11 Reliability of the data

In this chapter the accuracy, reliability and the confidence limits of the data given will be studied.

Questions to be answered are:

1. Is the population of the Second International Enquiry a representative set of data for all single pressure SF₆ gas circuit-breakers placed in service around the world?
2. Are, for the population considered, all major failures and minor failures reported via the CIGRE enquiry (completeness)?
3. What is the influence of sub-populations on the overall enquiry results (homogeneity)?
4. Are, from a statistical point of view, the (sub-)population(s) and the data for the cross references large enough (confidence limits)?
5. Was the enquiry clear enough and what is the influence of incorrect answers (accuracy)?
6. What is the stochastic characteristic of certain outcomes of the enquiry (distribution functions, average or median values, percentiles, comparisons)?
7. Which parameters have the largest influence on the outcome of the second enquiry?

2.11.1 Representative set of data

Although the number of circuit-breaker-years involved in the enquiry is low compared with the world-wide population, it is expected that the population of 70708 circuit-breaker-years during four years is representative enough for the worldwide situation during the years of the survey. The participating utilities are spread over the world and the sub-populations they have brought in are estimated to be more or less proportional to the market share of those regions in the world.

The magnitude of the population of the Second Enquiry is comparable with that of the First Enquiry, but it is more representative for the worldwide situation.

2.11.2 Completeness

The MF-rates and mf-rates per participating country show a large range. The MF-rates per country vary from 0.13 per 100 circuit-breaker-years to 8.4 and the mf-rates vary from 43 per 100 circuit-breaker-years to 0.1 (see Figure 2.9.1.2.). The average value of the MF-rates per country is 1.53 and the median 0.71 per 100 circuit-breaker-years, compared with the overall MF-rate of 0.67 per 100 circuit-breaker-years.

The large differences between the countries for the MF-rates and mf-rates forms an indication that not every country is weighting failures and defects in the same way. When deleting the countries with less than 1000 circuit-breaker-years, the MF-rates vary from 0.13 to 2.69 per 100 circuit-breaker-years and the average value of the MF-rates per country is 1.03, while the median value equals 0.84 per 100 circuit-breaker-years.

An evaluation of the MF-rate of the complete population minus one country, shows a large influence of a particular country. Table 2.11.1 gives the MF-rates with some countries excluded. The countries A, B and C are the countries with the largest, the second largest and the third largest subpopulation respectively.

Table 2.11.1 : Major failure rates with some countries excluded

Population	Major failures per 100 cb-years
Complete	0.67
Minus country A	0.99
Minus country B	0.75
Minus country C	0.67

cb = circuit-breaker

As with the First Enquiry, an evaluation has been made for the complete population without the countries with the highest and the lowest sub-population and without the countries with the highest and the lowest MF-rate. The results are presented in Table 2.11.2.

Similar studies in the First Enquiry have also lead to

the estimation that the MF-rate may vary up to +50%.

From the mf/MF ratio it is concluded that the response to the minor failures is better than in the First Enquiry (see Figure 2.10.1.1.). It is also expected that the response to the major failures is more accurate than in the First Enquiry due to the stimulating effect of the CIGRE representative.

Table 2.11.2 : Major failure rates with particular countries excluded

Population	Major failures per 100 cb-years
Complete	0.67
without lowest/highest subpopulation	0.99
without lowest/highest MF-rate	0.95

cb = circuit-breaker
MF = Major failure

2.11.3 Homogeneity

Another split up in subdivisions is to determine the MF-rates for ME versus NME circuit-breakers. These sub-populations can be divided into other groups, such as per location (in-/outdoors), per age (installed before/after 1.1.83), per operating mechanism (hydraulic/pneumatic/springs) or per voltage range (below/above 100 kV). MF-rates have also been calculated for even smaller sub-populations; i.e. combinations of these peculiarities. (See also Table 2.9.2.5.)

The MF rate for ME is 0.32 per 100 circuit-breaker years and for NME 0.94, while the whole population has a MF rate of 0.67 failures per 100 circuit-breaker-years. The largest influence is coming from the sub-population ME with a voltage range below 100 kV. Without this sub-population the MF-rates are: for ME 0.61 per 100 circuit-breaker years and for the whole population 0.85. The reason of this difference can be found in the non-homogeneity of the population.

Other sub-populations do not substantially influence the failure rates. Therefore, considering the data given in chapter 2.11.2, it can be estimated that a more realistic overall MF-rate is closer to 0.9 per 100 circuit-breaker-years than to 0.7.

2.11.4 Confidence limits

Although the circuit-breaker sub-populations will show more homogeneity than the complete population, the reliability of the failure rates may vanish as the magnitude of the subgroups may become too small for a statistical analysis. The influence of inhomogeneous sub-populations on the results of the whole population is limited, as has been shown in the last paragraph. The largest influence is coming from the sub-population of metal enclosed circuit-breakers with a rated voltage below 100 kV.

Another large influence is coming from the countries with the highest population. Therefore three cases should be considered: one with the premise of a complete homogeneous population of 70708 circuit-breaker-years, one with the premise of a homogeneous population of 54522 circuit-breaker-years (i.e. minus the metal enclosed circuit-breakers below 100 kV) and one without the countries with the highest and the lowest population (45907 circuit-breaker-years). The point estimates for the number of major failures are respectively 475, 464 and 455. According to IEC 605.4 the 90% confidence limits can be calculated and the minimum and maximum failure rates under the assumption of an homogeneous population. The results are presented in Table 2.11.3.

Table 2.11.3 : 90% confidence limits for number of major failures

Case	Population	Minimum	Point estimates	Maximum
1	70708	440	475	510
2	54522	429	464	499
3	45907	420	455	490

Table 2.11.4 : Min. and max. estimation of the major failure rate per 100 cby

Case	Population	Minimum estimation	Estimation	Maximum estimation
1	70708	0.62	0.67	0.72
2	54522	0.79	0.85	0.92
3	45907	0.91	0.99	1.07

cby = circuit-breaker-years

The 90% confidence limits lead to minimum and maximum estimation of the major failure rate as presented in Table 2.11.4 .

Per failure mode the 90% confidence limits will show a relatively wider range than for the complete population. The next paragraph will consider the effects of the minimum and maximum failure rates per characteristic. It should be pointed out that the figures shown assume an homogeneous population.

The actual population is not homogeneous due to the fact that circuit-breakers are different from the point of view of design, manufacture and application and that their maintenance in service is different; the results can therefore have a wider spread than shown in the tables.

2.11.5 Accuracy

The accuracy of the filled out enquiry forms can be deduced from the contradictions that appear within the cross-correlation tables (Chapter 2.10.). Misinterpretation of the enquiry forms is the major cause of inaccuracies. Another chapter is dealing with these misinterpretations and the necessary improvements of the failure cards. (Chapter 11)

Some inaccuracies can be seen in the cross-correlation tables of the origin of the failure and the sub-assembly responsible for the failure. But more important is the accuracy of the table giving the failure characteristics. The crosscorrelation tables of the failure modes and the origin or the sub-assembly responsible reveal some misinterpretations.

The conclusions from studies in depth of the cross-correlations are:

- * Some answers to the item *Does not make the current* should probably have been addressed to the item *Does not close on command* .
- * Some *Fails to carry the current* may be *Opens without command* .
- * Probably half of the locking failures are discovered at an attempt to operate the circuit-breaker and belong to the failure modes *Does not open or close on command* .
- * Some *Does not close on command* should possibly be *Locked in open position* .
- * Some *Breakdown across open pole (internal)* can be *Does not make or break the current* .

All corrections of the number of failures per failure mode are within the 90% confidence limits of that

particular number of failures.

The effects of the completeness, the non homogeneity, the confidence limits and the accuracy can be combined in the statement: the major failure rate is 0.8 ± 0.2 failure per 100 circuit-breaker years.

Together with the conclusions of the former paragraphs, the results of this study can be presented as in Table 2.11.5 .

Table 2.11.5 : Major failure rates per characteristics

Characteristic	Major failures per 100 cb-years
Does not close on command	0.2
Does not open on command	0.1
Closes without command	0.0
Opens without command	0.1
Does not make the current	0.0)
Does not break the current	0.0)
Fails to carry the current	0.0)
Breakdown to earth	0.0)0.1
Breakdown between poles	0.0)
Breakdown across open pole (internal)	0.0)
Breakdown across open pole (external)	0.0)
Locked in open or closed position	0.2
Others (Intervention in 30 Minutes)	0.1
Total major failure rate	0.8

cb = circuit-breaker

2.11.6 Distribution functions

One has to be careful with calculating and interpreting average values from the population data. Many data are based on estimated numbers. The statistical distribution of those data shows a wide spread.

An important group of parameters is the estimated average number of operating cycles (C-O) per year; and, for a particular circuit-breaker, the estimated

number of operating cycles since commissioning at the moment of the major failure and the estimated number of operating cycles since the last overhaul at the moment of the major failure. The selection of the percentile of the distribution of the number of operating cycles per year is also relevant in view of assessing the number of operations for the mechanical endurance type test. The median value of 30 cycles per year leads to a total of 750 cycles after 25 years and 1200 after 40 years. Other percentiles and the average are given in Table 2.11.6 .

Table 2.11.6 : Estimated number of operating cycles per year and per lifetime

Percentile	Number of oper. cycles per year	Number of oper. cycles after 25 years	Number of oper. cycles after 40 years
Average	42	1050	1680
50%	30	750	1200
75%	50	1250	2000
90%	76	1900	3040
95%	84	2100	3360

From the users point of view, the number of 2000 operations will fit well for 75% of all circuit-breakers during 40 years and for more than 90% during 25 years. These results confirm the necessity to increase the number of operating cycles in IEC Standards, as done after the First Enquiry. Therefore at present

time, the number of 2000 operating cycles is also required in IEC standard 56 as a mechanical endurance type test.

2.11.7 Influence of parameters

To prevent that misleading conclusions are drawn from the results of the Second International Enquiry, it is important to clarify in which order the different parameters do influence the outcome of the survey.

From the former chapters it can be concluded that the country with the largest circuit-breaker population strongly affects the results of the enquiry. The results of the data processing performed disregarding the countries having the highest and lowest circuit-breaker population show that an influent parameter is the voltage class; another important parameter is the type of operating mechanism. The influence of the age and the type of enclosure seems to be limited. As the number of indoor located non metal enclosed circuit-breakers is too little when we disregard the countries having the extreme circuit-breaker population, it is not possible to conclude about the influence of the type of location of the circuit-breakers on the reliability of the results.

To sum up, when considering the data of the Second International Enquiry, it is important to be aware of the influence of the different parameters, according to the following priority: the extension of the circuit-breaker population of each participating country, the voltage class and the type of the operating mechanism.

3. IMPACT OF THE TYPE OF OPERATING MECHANISM ON THE RELIABILITY

3.1 Introduction

This chapter forms part of a CIGRE Technical Brochure. In conjunction with the introduction to this brochure it can be read as a separate document.

The total number of circuit-breaker-years, the circuit-breaker population, on which the following study is based, comprises 70708 single pressure SF₆ circuit-breaker-years in the voltage range of 63 kV up to 700 kV and above. The data was received from 132 utilities of 22 countries which answered the CIGRE questionnaire of the Second International Enquiry on single pressure SF₆ circuit-breaker failures and defects in service during the years 1988-1991. The circuit-breakers were described by their rated voltage, the year of installation, the type of location, the type of enclosure and the type of operating mechanism. Each failure was identified by the circuit-breaker component and the stress responsible for it and classified according to a list of suggested failure modes, origins and causes. In addition, information on the consequences of the major failures in terms of circuit-breaker downtime, the time required to obtain spare parts and the existence of a fire and/or explosion of the circuit-breaker was also provided.

The reliability of a circuit-breaker is very important to guarantee for the safety of the energy supply. The mechanical drive systems of the switchgear have to fulfil the required operations under all electrical and mechanical aspects for a long period of service time of more than 20 years.

The objectives of this study concerning the mechanical failures on circuit-breaker drive systems are

- to give a general information about the major and minor failures distribution and the impact of the drive on the reliability of the circuit-breaker (chapter 3.3)
- to check which correlations do exist between the type of the operating mechanism and the causes of failures and the failure modes (chapter 3.4)
- to give reliability data (chapter 3.5)
- to find out about the differences of drive failures on metal enclosed vs. non metal enclosed circuit-breakers (chapter 3.6)
- to evaluate the contribution of environmental conditions and number of operations on the failures of drive systems (chapter 3.7)

- to conclude about the necessity of improvements of testing and/or diagnostics on drive systems or their components (chapter 3.8)
- to draw final conclusions (chapter 3.9)

3.2 Circuit-breaker drive systems

Circuit-breakers have very specific requirements on the drive energy and the operational behaviour. Therefore special drive systems have been developed for circuit-breakers all the times. The reliability of the drive mechanism is an important part of the disturbance free operation of the circuit-breaker. Already as a result of the First International Enquiry during the years 1974 to 1977, which included all technologies of circuit-breakers at service voltages of 63kV and above, it was found that about 70% of all failures were of mechanical origin including the drive, its controls and the auxiliary equipment. However not all of them are related to the operating mechanism.[1]

While in the First Enquiry no specific information about the drive was collected, it was asked in the Second Enquiry, which covered only single pressure SF₆-gas circuit-breakers at service voltages of 63kV and above, for the type of drive of the circuit-breaker.

In this report three types of drives are distinguished:

- A : Hydraulic mechanisms, which may include springs
- B : Pneumatic mechanisms, which may include springs
- C : Spring operated mechanisms

The distribution of the different kind of drives on all SF₆ single pressure circuit-breakers can be seen in table 3.2.1.

If we split the population according to the different voltage levels we will get the distribution of types of drives as presented in Table 3.2.2.

It has to be considered that circuit-breakers having a rated voltage below and including 170 kV will have normally a common drive for all three poles and that for breakers above 200 kV single pole drives are used. So the population of drives is different from the circuit-breaker population. 25% of all circuit-breakers

Table 3.2.1 : Distribution of type of drives for the whole population

Type of drive	Number of circuit-breaker-years	Distribution (%)
A : Hydraulic	36382	51.4
B : Pneumatic	21258	30.1
C : Spring	13068	18.5
Total:	70708	100.0

Table 3.2.2 : Number of circuit-breaker-years for the different voltage levels

Voltage (kV)	Operating mechanism					
	Type A		Type B		Type C	
	Number of circuit-breaker-years	Percentage (%)	Number of circuit-breaker-years	Percentage (%)	Number of circuit-breaker-years	Percentage (%)
63 ≤ V < 100	8529		9678		6148	
100 ≤ V < 200	11048		6462		6010	
Sub-Total: 63 ≤ V < 200	19577	27.7	16140	22.8	12158	17.2
200 ≤ V < 300	8284		2205		444	
300 ≤ V < 500	7194		2261		462	
500 ≤ V < 700	1267		624		4	
700 ≤ V	60		28		0	
Sub-Total: 200 ≤ V	16805	23.7	5118	7.3	910	1.3
Total:	36382	51.4	21258	30.1	13068	18.5

with a rated voltage below 200kV use a spring operated mechanism, however above 200kV less than 5% of all circuit-breakers use spring mechanisms but 70% use a hydraulic drive.

3.3 Impact of the drive on the reliability of the circuit-breaker

In total 475 major failures (MF) and 3358 minor failures (mf) were reported in the Second Enquiry. This result includes all circuit-breakers metal enclosed and non metal enclosed types on indoors and outdoors location.

For a better comparison the results of the first enquiry are also included. The distribution of the origin of all failures is given in Tables 3.3.1 and 3.3.2.

It is obvious that more than the mechanical drive is responsible for all these failures. However a significant percentage of the failures is of this origin. Still more than 50% of all major failures in the second enquiry are mechanical failures compared with about 70% in the first enquiry. However the tightness of the SF₆ gas system can also be regarded as possibly originated by mechanical defects.

85.6% mechanical minor failures from the First Enquiry were reduced to 49.3% of this origin in the second enquiry. However the impact of the SF₆ tightness needs to be considered when comparing these figures.

For the following evaluations only mechanical failures on operating mechanisms will be regarded. In total 203 major failures and 1275 minor failures are reported as failures on mechanical operating mechanism systems in the Second Enquiry.

Table 3.3.1 : Origin of major failures in %

	Percentage (%)			
	Second Enquiry			First Enquiry
	Placed in service 1.1.78 - 1.1.83	Placed in service after 1.1.83	All period	All period
Mechanical in operating mechanism (earthed)	30.4	48.6	44.0	
Mechanical in other parts of the circuit-breaker	14.8	9.0	10.4	
Sub-Total: Mechanical failures	45.2	57.6	54.4	70.1
Electrical (main circuit)	12.2	14.5	13.9	10.6
Electrical (auxiliary and control circuit)	29.6	22.8	24.5	19.1
Tightness of SF6-gas system	13.0	5.2	7.2	1)
Total: Percentage			100%	100%
Number of major failures			475	1231

1) Not specified

Table 3.3.2 : Origin of minor failures in %

	Percentage (%)			
	Second Enquiry			First Enquiry
	Placed in service 1.1.78 - 1.1.83	Placed in service after 1.1.83	All period	All period
Mechanical in operating mechanism (earthed)	32.0	43.2	39.4	
Mechanical in other parts of the circuit-breaker	9.6	10.0	9.9	
Sub-Total: Mechanical failures	41.6	53.2	49.3	85.6
Electrical (main circuit)	1.0	0.8	0.9	2.7
Electrical (auxiliary and control circuit)	9.6	10.5	10.2	11.7
Tightness of SF6-gas system	47.8	35.4	39.6	1)
Total: Percentage			100%	100%
Number of minor failures			3358	1641

1) Not specified

3.4 Correlations with the failure modes and causes

From the total number 44.0% of all major failures and 39.4% of all minor failures are of the origin *Mechanical in Operating Mechanism*. This indicates very clearly the impact of the operating mechanism on the reliability of the circuit breaker. The operating mechanism for metal enclosed and non metal enclosed switchgear is normally of the same type.

Therefore they are not under consideration separately concerning their causes and modes.

If we look for the distribution of failures of the different types of operating mechanism, we will get the result as presented in Table 3.4.1 .

This distribution over the different types of drives has to be related to the population and will be evaluated in the next chapter (3.5 Reliability Data).

Table 3.4.1 : Distribution of failures of the different types of operating mechanism versus voltage level

Voltage (kV)	Operating mechanism					
	Type A		Type B		Type C	
	Number of major failures	Number of minor failures	Number of major failures	Number of minor failures	Number of major failures	Number of minor failures
All voltages	111	1053	57	170	35	52
63 ≤ V < 100	6	192	13	31	7	9
100 ≤ V < 200	50	379	12	54	17	18
200 ≤ V < 300	19	149	17	40	4	10
300 ≤ V < 500	28	246	7	33	7	15
500 ≤ V < 700	8	85	6	12	0	0
700 ≤ V	0	2	2	0	0	0

Table 3.4.2 : Characteristics of the mechanical major failures versus the different types of operating mechanism

	Operating mechanism					
	Type A		Type B		Type C	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers
Does not close on command	18.0	20	24.6	14	45.7	16
Does not open on command	11.7	13	1.8	1	5.7	2
Closes without command	2.7	3	1.8	1	2.9	1
Opens without command	9.0	10	5.3	3	17.1	6
Does not make the current	2.7	3	0.0	0	0.0	0
Does not break the current	0.0	0	0.0	0	2.9	1
Fails to carry the current	0.0	0	0.0	0	0.0	0
Breakdown to earth	0.0	0	0.0	0	0.0	0
Breakdown between poles	0.0	0	0.0	0	0.0	0
Breakdown across open pole (internal)	0.0	0	7.0	4	2.9	1
Breakdown across open pole (external)	0.0	0	0.0	0	0.0	0
Locking in open or closed position	44.1	49	28.1	16	11.4	4
Others	11.7	13	31.6	18	11.4	4
Total number of received answers		111		57		35

Major and minor failures on drive systems have typical failure modes, which can be taken from Tables 3.4.2 and 3.4.3 .

The different types of drives have significant differences in their failure modes. In conclusion from table 3.4.2 the following statements can be made:

- The highest risk of a major failure of a hydraulic or pneumatic drive is *locked in open or closed position*.

However an alarm that the circuit-breaker has been locked leads to the failure mode *Locked in open or closed position*, while the detection that the circuit-breaker has been locked at a command to operate leads to the failure mode *Does not open or close on command*. So in general the hydraulic and the pneumatic drive have a certain risk to reject the operation on command.

- The highest risk of a spring drive is *Does not open*

Table 3.4.3 : Characteristics of the mechanical minor failures versus the different types of operating mechanism

	Operating mechanism					
	Type A		Type B		Type C	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers
Air or hydr. oil leakage in op.mech.	69.2	726	65.3	109	3.8	2
Small SF6 leakage due to corrosion	0.2	2	1.2	2	1.9	1
Small SF6 leakage due to other causes	1.7	18	1.2	2	5.8	3
Change in functional characteristics	15.8	166	7.8	13	48.1	25
Other	13.1	137	24.6	41	40.4	21
Total number of received answers 1)		1049		167		52

1) Equal to 99.5% of all the mf having a mechanical origin in the operating mechanism

mf = minor failure

or close on command.

- The probability that failures occur in the electrical main circuit is very low. Only the major failure modes *Does not make the current* of the hydraulic drive, *Breakdown across open poles* of the pneumatic drive and *Does not break the current* and *Breakdown across open poles* of the spring drive mechanism are responsible for electrical failure modes.

The minor failures show a different failure mode due to their different definition. Here it can be seen in Table 3.4.3 that most of the minor failures are either hydraulic or air leakages (hydraulic and pneumatic drives) or will lead to a change in the functional characteristics (spring drive).

The causes of the mechanical failures with respect to the different periods for which the collection of the data took place can be taken from the Tables 3.4.4 and 3.4.5.

Table 3.4.4 : Cause of mechanical major failures

	All voltages					
	Placed in service 1.1.78-1.1.83		Placed in service After 1.1.83		All period	
	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)	No. of answers
Design	14.3	5	37.1	62	33.2	67
Manufacture	28.6	10	27.5	46	27.7	56
Inadequate instruction for erect., oper., maint.	0.0	0	2.4	4	2.0	4
Incorrect erection	5.7	2	6.6	11	6.4	13
Incorrect operation	17.1	6	4.2	7	6.4	13
Incorrect maintenance	8.6	3	0.0	0	1.5	3
Stresses beyond those specified	0.0	0	3.0	5	2.5	5
Other external causes	0.0	0	2.4	4	2.0	4
Other	25.7	9	16.8	28	18.3	37
Total number of received answers		35		167		202
		1)		2)		3)

1) Equal to 100% of MF of all the countries

MF = major failure

2) Equal to 99.4% of MF of all the countries

3) Equal to 99.5% of MF of all the countries

Table 3.4.5 : Cause of mechanical minor failures

	All voltages					
	Placed in service 1.1.78-1.1.83		Placed in service After 1.1.83		All period	
	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)	No. of answers
Design	23.1	80	17.5	161	19.0	241
Manufacture	31.8	110	41.5	382	38.9	492
Inadequate instruction for erect., oper., maint.	2.0	7	3.7	34	3.2	41
Incorrect erection	2.9	10	11.5	106	9.2	116
Incorrect operation	3.8	13	4.6	42	4.3	55
Incorrect maintenance	6.4	22	3.5	32	4.3	54
Stresses beyond those specified	4.6	16	2.0	18	2.7	34
Other external causes	9.0	31	4.9	45	6.0	76
Other	16.5	57	10.9	100	12.4	157
Total number of received answers		346		920		1266
		1)		2)		3)

1) Equal to 98.8% of mf of all the countries

2) Equal to 99.5% of mf of all the countries

3) Equal to 99.3% of mf of all the countries

mf = minor failure

However the more important question is the cause of the major and minor failures on the different kind of operating mechanism, which will be answered by Tables 3.4.6 and 3.4.7

The biggest part of all failures is caused by design and manufacture. It should be checked carefully the reliability of operating mechanisms in type test and

routine testing.

18.8% of the major failures and 23.7% of the minor failures are also human caused failures with their failure modes *Inadequate instruction, incorrect erection, operation or maintenance and Stresses beyond those specified*, which cannot be prevented by development improvements but only influenced by better

Table 3.4.6 : Cause of mechanical major failures on different kind of operating mechanism

	Operating mechanism					
	Type A		Type B		Type C	
	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)	No. of answers
Design	31.8	35	40.4	23	25.7	9
Manufacture	22.7	25	31.6	18	37.1	13
Inadequate instruction for erect., oper., maint.	1.8	2	3.5	2	0.0	0
Incorrect erection	8.2	9	1.8	1	8.6	3
Incorrect operation	8.2	9	0.0	0	11.4	4
Incorrect maintenance	1.8	2	1.8	1	0.0	0
Stresses beyond those specified	3.6	4	1.8	1	0.0	0
Other external causes	3.6	4	0.0	0	0.0	0
Other	18.2	20	19.3	11	17.1	6
Total number of received answers 1)		110		57		35

1) Equal to 99.5% of MF of all the countries

MF = major failure

Table 3.4.7 : Cause of mechanical minor failures on different kind of operating mechanism

	Operating mechanism					
	Type A		Type B		Type C	
	Percentage (%)	No. of answers	Percentage (%)	No. of answers	Percentage (%)	No. of answers
Design	18.5	193	20.6	35	25.5	13
Manufacture	38.4	401	41.2	70	41.2	21
Inadequate instruction for erect., oper., maint.	2.9	30	5.9	10	2.0	1
Incorrect erection	9.2	96	7.1	12	15.7	8
Incorrect operation	5.3	55	0.0	0	0.0	0
Incorrect maintenance	4.2	44	5.3	9	2.0	1
Stresses beyond those specified	2.4	25	4.1	7	3.9	2
Other external causes	5.4	56	10.0	17	5.9	3
Other	13.9	145	5.9	10	3.9	2
Total number of received answers 1)		1045		170		51

1) Equal to 99.3% of mf of all the countries

mf = minor failure

instructions, documentation and training.

The correlation between the characteristics of the major failures and the identification of the sub-assembly or component responsible for it will be given in the next paragraph.

3.5 Reliability data

As the operating mechanism and the electrical control and auxiliary circuits are responsible for most

of the failures they are considered to be items of special interest. Therefore an extended set of tables gives information with respect to the special mode *Mechanical failures on different types of operating mechanism.*

The percentage values are calculated with reference to the number of all failures of mechanical drive origin. To get the right impression about the reliability of the circuit-breaker dependant on the different type of drive the basis has to be the number of circuit-breaker years of Table 3.2.2. Table 3.5.1 and Table 3.5.2 contain the major and minor failure rates

Table 3.5.1 : Mechanical major failure rates for the different types of operating mechanism

Voltage (kV)	Operating mechanism Type A			Operating mechanism Type B			Operating mechanism Type C		
	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years
All voltages	36382	111	0.31	21258	57	0.27	13068	35	0.27
63 ≤ V < 100	8529	6	0.07	9678	13	0.13	6148	7	0.11
100 ≤ V < 200	11048	50	0.45	6462	12	0.19	6010	17	0.28
200 ≤ V < 300	8284	19	0.23	2205	17	0.77	444	4	0.90
300 ≤ V < 500	7194	28	0.39	2261	7	0.31	462	7	1.52
500 ≤ V < 700	1267	8	0.63	624	6	0.96	4	0	0.00
700 ≤ V	60	0	0.00	28	2	7.14	0	0	0.00

A: Hydraulic mechanism, which may include spring

B: Pneumatic mechanism, which may include spring

C: Spring operated mechanism

cb = circuit-breaker

Table 3.5.2 : Mechanical minor failure rates for the different types of operating mechanism

Voltage (kV)	Operating mechanism Type A			Operating mechanism Type B			Operating mechanism Type C		
	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years
All voltages	36382	1053	2.89	21258	170	0.80	13068	52	0.40
63 ≤ V < 100	8529	192	2.25	9678	31	0.32	6148	9	0.15
100 ≤ V < 200	11048	379	3.43	6462	54	0.84	6010	18	0.30
200 ≤ V < 300	8284	149	1.80	2205	40	1.81	444	10	2.25
300 ≤ V < 500	7194	246	3.42	2261	33	1.46	462	15	3.25
500 ≤ V < 700	1267	85	6.71	624	12	1.92	4	0	0.00
700 ≤ V	60	2	3.33	28	0	0.00	0	0	0.00

A: Hydraulic mechanism, which may include spring

cb = circuit-breaker

B: Pneumatic mechanism, which may include spring

C: Spring operated mechanism

for the different types of operating mechanism whereas Tables 3.5.3 and 3.5.4 show the failure rates with respect to the different periods for which collection of data took place. The circuit-breakers installed between 1.1.78 and 1.1.83 show a better reliability than those installed after 1.1.83.

The major failure rate of all types of drives is between 0.27 (pneumatic and spring drive) to 0.31 (hydraulic drive). The minor failure rate of hydraulic drive systems is with 2.89 higher than of the other types of drives with 0.80 for pneumatic and 0.40 for spring drives.

Under the assumption, that the drive energy will increase with the voltage level, it should be crosschecked, whether the failure rate shows significant differences dependant on the voltage level. It shows, that the major and minor failure rate

have a tendency to increase with higher rated voltage for all kinds of operating mechanisms. However this tendency is most obvious for spring drive mechanisms.

The correlation between the failure mode *Mechanical in operating mechanism (earthed)* for the major and minor failures and the component responsible for the failure can be seen from Table 3.5.5. The distribution of major failures among the components of the operating mechanism is quite the same, for minor failures the elements *Compressor, motor, pump* and *Control elements* are the most critical ones.

From Table 3.4.3 we know already that about 66% of all minor failures are leakages. So in general the tightness of hydraulic and pneumatic systems has to be improved.

Table 3.5.3 : Rates of mechanical major failures for the different periods of collection

Voltage (kV)	Placed in service 1.1.78-1.1.83			Placed in service after 1.1.83			All period		
	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years
All voltages	21157	35	0.17	49551	168	0.34	70708	203	0.29
63 ≤ V < 100	7057	4	0.06	17298	22	0.13	24355	26	0.11
100 ≤ V < 200	6365	14	0.22	17155	65	0.38	23520	79	0.34
200 ≤ V < 300	3515	9	0.26	7418	31	0.42	10933	40	0.37
300 ≤ V < 500	3462	8	0.23	6455	34	0.53	9917	42	0.42
500 ≤ V < 700	755	0	0.00	1140	14	1.23	1895	14	0.74
700 ≤ V	3	0	0.00	85	2	2.35	88	2	2.27

cb = circuit-breaker

Table 3.5.4 : Rates of mechanical minor failures for the different periods of collection

Voltage (kV)	Placed in service 1.1.78-1.1.83			Placed in service after 1.1.83			All period		
	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years	Sample size (cb-years)	Number of failures	Failures per 100 cb-years
All voltages	21157	350	1.65	49551	925	1.87	70708	1275	1.80
63 ≤ V < 100	7057	22	0.31	17298	210	1.21	24355	232	0.95
100 ≤ V < 200	6365	159	2.50	17155	292	1.70	23520	451	1.92
200 ≤ V < 300	3515	59	1.68	7418	140	1.89	10933	199	1.82
300 ≤ V < 500	3462	99	2.86	6455	195	3.02	9917	294	2.96
500 ≤ V < 700	755	11	1.46	1140	86	7.54	1895	97	5.12
700 ≤ V	3	0	0.00	85	2	2.35	88	2	2.27

cb = circuit-breaker

Table 3.5.5 : Identification of the sub-assembly or component responsible for the mechanical failures of the operating mechanism

	Major failures						Minor failures					
	Operation mechanism						Operating mechanism					
	Type A		Type B		Type C		Type A		Type B		Type C	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers
Compressor, motors, pumps, pipework	27.2	31	50.0	30	10.0	3	40.2	470	59.8	134	19.3	11
Energy storage (accumulator, spring)	23.7	27	8.3	5	13.3	4	18.1	211	5.4	12	26.3	15
Control elements (non electrical)	19.3	22	26.7	16	20.0	6	30.2	353	13.4	30	0.0	0
Actuators and damping device	20.2	23	13.3	8	36.7	11	9.6	112	13.4	30	45.6	26
Mechanical transmission	9.6	11	1.7	1	20.0	6	1.9	22	8.0	18	8.8	5
Total number of answers		114		60		30		1168		224		57

3.6 Comparison of failures on drives of metal enclosed versus non metal enclosed circuit-breakers

The drives used for the operation of circuit-breakers are normally the same for metal enclosed (ME) and non metal enclosed (NME) breakers. However differences can be seen if we compare the failure rates of both types of equipment. This comparison is made in Tables 3.6.1 and 3.6.2. For both the major and the minor failures the failure rate for non metal enclosed circuit-breakers is higher than for metal enclosed breakers. While the factor for the hydraulic drive is nearly the same it is for pneumatic and spring drive mechanisms significantly higher. However, the ME-NME data should be read with great

care (see also chapter 2.11 and 5).

3.7 Impact of environmental conditions and number of operations

The majority of all circuit-breakers is outdoor located (85,2%), however for 90.0% of all major failures and 97.9% of all minor failures no environmental stresses were presumed to contribute to the failure. Tables 3.7.1 and 3.7.2 give the location of the circuit-breakers concerning the mechanical failures on operating mechanism.

Figures about stresses presumed contributing to the mechanical failures will be found in Tables 3.7.3, 3.7.4 and 3.7.5.

Table 3.6.1 : Comparison of major failure rates of non metal enclosed versus metal enclosed circuit-breakers

	Operating mechanism					
	Type A		Type B		Type C	
	Metal enclosed	Non metal enclosed	Metal enclosed	Non metal enclosed	Metal enclosed	Non metal enclosed
Circuit-breaker-years	10258	26124	13138	8120	7004	6064
Number of major failures	22	89	13	44	7	28
Failures per 100 circuit-breaker-years	0.21	0.34	0.10	0.54	0.10	0.46
Ratio Non metal enclosed / metal enclosed	1.6		5.4		4.6	

Table 3.6.2 : Comparison of minor failure rates of non metal enclosed versus metal enclosed circuit-breakers

	Operating mechanism					
	Type A		Type B		Type C	
	Metal enclosed	Non metal enclosed	Metal enclosed	Non metal enclosed	Metal enclosed	Non metal enclosed
Circuit-breaker-years	10258	26124	13138	8120	7004	6064
Number of minor failures	265	788	59	111	6	46
Failures per 100 circuit-breaker-years	2.58	3.02	0.45	1.37	0.09	0.76
Ratio Non metal enclosed / metal enclosed	1.2		3.0		8.4	

Table 3.7.1 : Location of the circuit-breaker concerning the mechanical major failures on operating mechanism

Voltage (kV)	Location Indoors						Location Outdoors					
	Op.mechanism		Op.mechanism		Op.mechanism		Op.mechanism		Op.mechanism		Op.mechanism	
	Type A		Type B		Type C		Type A		Type B		Type C	
	Sample size (cb-years)	Number of failures	Sample size (cb-years)	Number of failures	Sample size (cb-years)	Number of failures	Sample size (cb-years)	Number of failures	Sample size (cb-years)	Number of failures	Sample size (cb-years)	Number of failures
All voltages	4116	14	4533	5	1851	4	32266	97	16725	52	11217	31
63 ≤ V < 100	755	1	2755	2	756	2	7774	5	6923	11	5392	5
100 ≤ V < 200	1759	5	1144	1	1043	2	9289	45	5318	11	4967	15
200 ≤ V < 300	213	0	168	1	18	0	8071	19	2037	16	426	4
300 ≤ V < 500	1162	6	451	1	34	0	6032	22	1810	6	428	7
500 ≤ V < 700	227	2	15	0	0	0	1040	6	609	6	4	0
700 ≤ V	0	0	0	0	0	0	60	0	28	2	0	0

cb = circuit-breaker

The estimated average numbers of operating cycles since placed in service up to the moment a major failure occurred in correlation to the voltage level are

collected in Table 3.7.6 . From this table it can be seen that on average major failures occurred after a few hundred operating cycles.

Table 3.7.2 : Location of the circuit-breaker concerning the mechanical minor failures on operating mechanism

Voltage (kV)	Location Indoors						Location Outdoors					
	Op.mechanism		Op.mechanism		Op.mechanism		Op.mechanism		Op.mechanism		Op.mechanism	
	Type A		Type B		Type C		Type A		Type B		Type C	
	Sample size (cb-years)	Number of failures	Sample size (cb-years)	Number of failures	Sample size (cb-years)	Number of failures	Sample size (cb-years)	Number of failures	Sample size (cb-years)	Number of failures	Sample size (cb-years)	Number of failures
All voltages	4116	175	4533	14	1851	1	32266	878	16725	156	11217	51
63 ≤ V < 100	755	1	2755	6	756	1	7774	191	6923	25	5392	8
100 ≤ V < 200	1759	69	1144	2	1043	0	9289	310	5318	52	4967	18
200 ≤ V < 300	213	5	168	0	18	0	8071	144	2037	40	426	10
300 ≤ V < 500	1162	40	451	6	34	0	6032	206	1810	27	428	15
500 ≤ V < 700	227	60	15	0	0	0	1040	25	609	12	4	0
700 ≤ V	0	0	0	0	0	0	60	2	28	0	0	0

cb = circuit-breaker

Table 3.7.3 : Stress presumed contributing to the mechanical failure or defect: Ambient temperature

	Major Failures		Minor Failures	
	(%)	Number of answers	(%)	Number of answers
No contribution	96.6	196	98.8	1260
Contribution	3.4	7	1.2	15

Table 3.7.4 : Stress presumed contributing to the mechanical failure or defect: Environmental condition

	Major Failures		Minor Failures	
	(%)	Number of answers	(%)	Number of answers
No contribution	90.0	181	97.9	1237
Strong wind	0.0	0	0.1	1
Rain	0.0	0	0.2	2
Sudden variation in temperature	4.5	9	0.4	5
Snow, ice or hoar-frost	0.5	1	0.2	2
Corrosive atmosphere	0.0	0	0.2	3
Fog or high humidity	1.0	2	1.0	13
Pollution including dust	0.5	1	0.0	0
Lightning	1.0	2	0.0	0
Others	2.5	5	0.1	1
Total number of received answers		201		1264
		1)		2)

1) Equal to 99% of MF of all the countries

2) Equal to 99.1% of mf of all the countries

MF = major failure

mf = minor failure

Table 3.7.5 : Ambient temperature stress presumed contributing to the mechanical failure or defect on operating mechanism

Ambient temperature:	T<-25°C		-25°C<ST<-5°C		-5°C<ST<+5°C		+5°C<ST<+40°C		T>+40°C	
	(%)	No. of answers	(%)	No. of answers	(%)	No. of answers	(%)	No. of answers	(%)	No. of answers
Numbers for major failures 1)	0.0	0	28.6	2	28.6	2	42.9	3	0.0	0
Numbers for minor failures 2)	0.0	0	6.7	1	60.0	9	33.3	5	0.0	0

1) Total number of received answers for major failures: 7

2) Total number of received answers for minor failures: 15

Table 3.7.6 : Estimated average number of operating cycles since commissioning until a major failure occurred

Voltage (kV)	Percentile							
	Average	10%	25%	50%	75%	90%	95%	Maximum
All voltages	471	30	80	218	400	1102	1800	11579
63 ≤ V < 100	489	13	75	198	501	1800	2065	3140
100 ≤ V < 200	356	22	58	158	320	750	1355	5168
200 ≤ V < 300	471	30	143	250	507	923	1169	5584
300 ≤ V < 500	646	76	110	245	460	1252	1900	11579
500 ≤ V < 700	504	60	96	250	400	1649	1881	4008
700 ≤ V	125	8	8	50	200	240	240	240

3.8 Necessity of improvements in testing and/or diagnostics

Due to the number of operations of a circuit-breaker in service up to the failure as given in Table 3.7.6 it can be stated that all kind of major failures occur already after less than 500 operations in average. Conclusions on this should not be drawn for it has to be considered that the population data for this evaluation is not known.

However it seems not necessary to increase the number of operations for testing the circuit-breakers mechanical design during development (type test). 27.7% of the major failures and 38.9% of the minor failures (see Tables 3.4.4 and 3.4.5) were caused by manufacturing. In consequence it seems to be helpful to improve routine testing in these fields. However the impact of aging, corrosion or time in general can only be checked by tests partially.

In Table 3.8.1 it can be seen under which condition the mechanical major failure on operating mechanism was detected. Almost all major failures

and minor failures occur in service or available for service. Therefore diagnostics on mechanical drives must be recommended.

According to the most happened major failure modes (Table 3.4.2) special regards have to be taken on *Operation with or without command* and on *Locking*, and according to the minor failure modes (Table 3.4.3) on *Leakages* and *Changes in functional characteristics*.

3.9 Conclusions

- * For more than 50% of all circuit-breakers a hydraulic drive is used. 25% of all circuit-breakers with a rated voltage below 200kV use a spring operated mechanism, however above 200kV less than 5% of all circuit-breakers use spring mechanisms but 70% use a hydraulic drive.
- * 44.0% of all major failures and 39.4% of all minor failures have to be related to the mechanical drive. The drive is still the component with the most nu-

Table 3.8.1 : Condition of the circuit-breaker when the mechanical failure on operating mechanism was discovered

	Major failures						Minor failures					
	Operation mechanism						Operating mechanism					
	Type A		Type B		Type C		Type A		Type B		Type C	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers
In service or available for service	92.8	103	94.7	54	88.6	31	81.3	856	85.9	146	61.5	32
During maintenance	5.4	6	1.8	1	2.9	1	17.3	182	12.4	21	38.5	20
Other cases	1.8	2	3.5	2	8.6	3	1.4	15	1.8	3	0.0	0
Total number of received answers		111		57		35		1053		170		52

merous major failures.

- * The major failure rate of all types of drives is about the same: 0.3 failures per 100 circuit-breaker-years. The minor failure rate of hydraulic drives is about 7times higher and of the pneumatic drive is about 2times higher than for the spring drive. It shows, that the major and minor failure rate have a tendency to increase with higher rated voltage for all kinds of operating mechanisms. This tendency is most obvious for spring drive mechanism.
- * The highest risk for a major failure of a hydraulic or pneumatic drive is to be locked in open or closed position. The highest risk of a spring drive is a non-operation on command. However also the hydraulic and the pneumatic drive have a certain risk to reject the operation on command.
- * Most of the minor failures are either hydraulic or air leakages for hydraulic or pneumatic drives or will lead to a change of the functional characteristics of a spring drive mechanism.
- * The biggest part of all failures, that is 61% major failures and 58% minor failures, is caused by design and manufacture. However 19% of the major failures and 24% of the minor failures are human caused failures with their failure modes *Inadequate instruction, incorrect erection, operation or maintenance and Stresses beyond those specified*, which cannot be prevented by development

improvements but influenced by better instructions, documentation and training.

- * The components of the operating mechanism are all about the same responsible for the major failures, for minor failures the components *Compressor, motor, pump* and *Control elements* are the most critical ones. The influence of electrical auxiliary and control circuits and other control elements on major failures can be seen in Table 3.3.1.
- * About 66% of all minor failures are leakages. So in general the tightness of hydraulic and pneumatic systems has to be improved.
- * Almost all major failures and minor failures occur in service or available for service. Therefore diagnostics on mechanical drives must be recommended.

3.10 References

- [1] G.Mazza, R.Michaca
The First International Enquiry on Circuit-Breaker Failures and Defects in Service.
Electra No. 79, December 1981, pp.21-91

4. SF₆ TIGHTNESS AND GAS DENSITY SUPERVISION OF HIGH VOLTAGE CIRCUIT-BREAKERS

4.1 Introduction

This chapter forms part of a CIGRE Technical Brochure. In conjunction with the introduction to this brochure it can be read as a separate document.

The total number of circuit-breaker-years, the circuit-breaker population, on which the following study is based, comprises 70708 single pressure SF₆ circuit-breaker-years in the voltage range of 63 kV up to 700 kV and above. The data was received from 132 utilities of 22 countries which answered the CIGRE questionnaire of the Second International Enquiry on single pressure SF₆ circuit-breaker failures and defects in service during the years 1988-1991. The circuit-breakers were described by their rated voltage, the year of installation, the type of location, the type of enclosure and the type of operating mechanism. Each failure was identified by the circuit-breaker component and the stress responsible for it and classified according to a list of suggested failure modes, origins and causes. In addition, information on the consequences of the major failures in terms of circuit-breaker downtime, the time required to obtain spare parts and the existence of a fire and/or explosion of the circuit-breaker was also provided.

This chapter presents the results of SF₆ tightness of circuit-breakers and the behaviour of their gas density supervision. The objective of this document is to provide data on SF₆ tightness failures of circuit-breakers, to assess possible correlation of failures with the age of circuit-breaker, the type of enclosure, location and rated voltage. The contribution of the circuit-breaker components to the loss of tightness is also evaluated.

4.2 General information about SF₆ tightness and supervision

4.2.1 General principles

The breaking capacity and the dielectric withstand of circuit-breakers depend on SF₆ gas density. The gas density is checked on circuit-breakers with a density monitor.

Different events can lead to density variation detected by density monitor:

- SF₆ leakage itself,
- SF₆ adsorption by filtering products at low temperature,
- rapid and wide variations of temperature.

Only the first event corresponds to an actual failure. The second and third correspond to physical modifications inside the circuit-breaker but they do not have to lead to a signal from density monitor.

The density monitor installed on circuit-breakers detects the reduction of density. The parameter generally checked is the pressure and the corresponding pressure gauges are temperature-compensated. So the density monitor checks the pressure variation that is not due to temperature variation. With the progress of integrated electronic components, density gauges appear nowadays.

A circuit-breaker is normally fit out with three gas density monitors. There are some exceptions; very high voltage circuit-breakers can have 9 density monitors or more; on the contrary, small circuit-breakers can have only one density monitor for three poles.

The density monitor has generally two thresholds to signal an actual density loss. The function of the first threshold is to warn for a loss of density. The circuit-breaker can still be used but the operator must refill it before the signal of the second threshold that can occur few days later. The function of the second level is to lock or to open the circuit-breaker; below this level the circuit-breaker cannot be operated electrically. The gap between thresholds must be chosen to give enough time to refill circuit-breaker by operator in the case of a small leakage, and before reaching the second threshold. On the other hand, this gap should be large enough to avoid unexpected second level signal of density monitor.

4.2.2 The origins and the causes of SF₆ leakage

The density monitor indicates tightness failure of one circuit-breaker's pole but it does not indicate the position and the cause of the leakage. Further investigation and the repair can indicate the origin of the failure. The possible origins and causes are various, for example:

- corrosion near a seal,
- damage of a seal,
- impurity under a seal,
- porosity of metal component (casting, brazing...),
- break or crack of the enclosure (porcelain),

It must be noticed that *False SF6 leakage* can exist; it is due to physical event like important temperature variations, due to failure of density monitor, also due to incorrect refilling after maintenance. Moreover, every equipment has an accepted leakage rate which allows a minimum interval to be determined during which replenishment will not be required (typically 10-20 years). If the leakage exceeds this accepted rate, resulting in a need for more frequent replenishment, then this would be considered as a failure.

4.3 The Second International Enquiry

4.3.1 Enquiry about SF6 tightness and supervision

The Second International Enquiry on circuit-breaker failures gave a great attention to SF6 tightness of circuit-breakers. The results show that this topic is important: failures of SF6 tightness represent 40 % of all minor failures.

The following paragraphs analyse these results. General informations about SF6 tightness and about the Second International Enquiry are mentioned in sections 4.1 and 4.2.

4.3.2 Some recommendations for a better understanding of the results

As for all enquiries, the pertinence of the analysis depends on the consistency of data collected. This international enquiry has pointed out that practices vary from one country to another. This statement is particularly true when definitions are vague or ambiguous. This is particularly the case for failures of SF6 tightness. When a circuit-breaker does not close on command or when a component is broken, the attitude of the operator is clear, he mentions a failure. But each alarm of the density monitor is often treated differently.

The operator can,

- report a failure at each alarm, after having refilled the circuit-breaker,

Table 4.3.1 : Criteria to declare SF6 tightness failures

Utilities considering that there is a failure of SF6 tightness :	Number of answers	Percentage †
-at each signal of density monitor	15	53.6
-when frequency of signals increases	5	17.8
-only at each repair	8	28.6
Total:	28	100.0

Remark:

The answers come from utilities of the following countries: BELGIUM , BRAZIL , CZECHOSLOVAKIA , FRANCE , GERMANY , ITALY , JAPAN , NETHERLANDS , NORWAY , RUSSIA , SWITZERLAND.

- report a failure only when the frequency of alarms is high,
- report a failure only after having repaired the circuit-breaker

For this reason a special questionnaire was sent to all CIGRE representatives. The aim was to know the criteria considered by each utility to declare a SF6 tightness failure.

The results of this special questionnaire are summarized in Table 4.3.1 . The variety of these answers reinforces the care for the use of the data concerning tightness problems. If the goal would be to collect each alarm given by density monitor because this kind of information is linked to a failure of the circuit-breaker and repair becomes necessary, then failure rates presented in this document and obtained from the Second Enquiry must be considered as a minimum of the real behaviour of SF6 tightness.

4.4 The results of SF6 tightness

4.4.1 The variables considered

In this Second International Enquiry, circuit-breakers are mainly described by 5 parameters:

- voltage, from 63 kV to above 700 kV,
- enclosure technology, metal enclosed or non metal enclosed,
- location, indoor or outdoor,

- age, installed before 1983 (between 1/1/78 and 1/1/83) and after 1983 (between 1/1/83 and 1/1/92),
- operating mechanism, hydraulic or pneumatic or spring operating mechanism.

The objective of this paragraph is to present the tightness results and to analyse the influence of the first four parameters on tightness reliability. Operating mechanism has not been taken into account because this parameter has no influence on tightness. The influence of each parameter is obtained in cross-correlating parameters.

4.4.2 Origins and causes of major and minor failures

Table 4.4.1 presents the origin of all major failures. The SF6 tightness failures represent only 7 % of major failures. It is the lowest rate for all the origins of the enquiry. These good results can be explained by the on-line density monitor giving a warning to the operator before emergence of major failure.

Table 4.4.2 presents the origin of all minor failures. SF6 tightness represents 40 % of the origins of minor failures. It is the highest rate among all the origins of minor failures. As explained before, the on-line density monitor can avoid major failures by giving a warning to the operators, but consequently this monitoring leads to many minor failures being reported.

Considering the results of all minor failures, SF6 tightness failures are mainly:

- due to design or manufacture,
- detected when circuit-breakers are in service.

Table 4.4.3 presents the characteristics of the tightness major failures. Tightness major failures are not numerous, only 7 % of total, but when they appear they involve locking or automatic opening of circuit-breaker according to the choice for the function of the second threshold.

4.4.3 Correlation concerning SF6 tightness and voltage

The Table 4.4.4 shows the distribution of SF6 tightness failures (Major failures plus minor failures) according to the circuit-breaker rated voltage. For all the following paragraphs, major and

Table 4.4.1 : Origin of major failures

Origin of major failures	Number of failures	Percentage %
Mechanical in oper.mechanism (earthed)	203	44.0
Mechanical in other parts	48	10.4
Electrical (main circuit)	64	13.9
Electrical (aux. and control circuit)	113	24.5
Tightness of SF6 gas system	33	7.2
Total	461	100.0

Table 4.4.2 : Origin of minor failures

Origin of minor failures	Number of failures	Percentage %
Mechanical in oper.mechanism (earthed)	1275	39.4
Mechanical in other parts	319	9.9
Electrical (main circuit)	29	0.9
Electrical (aux. and control circuit)	330	10.2
Tightness of SF6 gas system	1280	39.6
Total	3233	100.0

minor failures have been added to analyse SF6 tightness because the number of major failures concerned with SF6 leakage is too small and is not meaningful from a statistical point of view.

The tightness of circuit-breakers belonging to the lowest range of voltage is better than for the higher voltages. The higher the voltage, the more numerous are breaker units and columns of circuit-breakers. This is unfavourable for reliability of the whole tightness system of the circuit-breaker and can explain the increase in the failure rate with higher voltages. This analysis is not sufficient to explain the results of the lower failure rate for voltages above 300 kV. The failure rate of tightness grows with voltage until 300-700kV range: for these classes result are better than the lower class 200-300kV. For a better understanding, Tables 4.4.5 through 4.4.7 provide some cross-correlations.

Table 4.4.5 presents results of voltage correlated with enclosure technology. In this case failure rate increases with voltage up to 200 kV for metal enclosed and up to 500 kV for non metal enclosed (not

Table 4.4.3 : Characteristics of SF6 tightness failures (major failures)

Characteristics of major failures	Number of SF6 tightness failures	Percentage %
Does not close on command	0	0.0
Does not open on command	1	3.2
Closes without command	0	0.0
Opens without command	5	16.1
Does not make the current	1	3.2
Does not break the current	2	6.5
Fails to carry the current	0	0.0
Breakdown to earth	0	0.0
Breakdown between poles	0	0.0
Breakdown across open poles (internal)	0	0.0
Breakdown across open poles (external)	1	3.2
Locking in open or closed position	18	58.1
Others	3	9.7
Total	31	100.0

Remark:

For 2 tightness failures no declaration of failure characteristics was given.

above 700 kV but this population is not meaningful from a statistical point of view).

Table 4.4.6 presents voltage correlated with location. In this case, failure rate increases with voltage until 300-700 kV for outdoor installation (except for more than 700 kV ; in that case failure rate is the highest) but decreases with voltage for indoor installation except for 500-700 kV range.

Table 4.4.7 shows results for voltage correlated with age. Failure rate increases with voltage until 300-700 kV for circuit-breakers manufactured before or after 1983.

All the above results show that SF6 tightness

Table 4.4.4 : SF6 tightness failures per voltage Major and minor failures

Voltage (kV)	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years
All Voltages	70708	1313	1.86
63 ≤ V < 100	24355	211	0.87
100 ≤ V < 200	23520	394	1.68
200 ≤ V < 300	10933	403	3.69
300 ≤ V < 500	9917	280	2.82
500 ≤ V < 700	1895	21	1.11
700 ≤ V 1)	88	4	4.55

cb = circuit-breaker

1) The sample size is too small for a reliable result

depends on technology and environment of circuit-breakers; multiplication of components is unfavourable. The volume of gas enclosure controlled by density monitor must be considered. For a constant quantity of SF6 escaping, the larger is the volume of the enclosure, the slower is the leakage.

The interpretation of these results must be done with prudence and discrimination. It would be imprudent to conclude that the ideal circuit-breaker would be built with only one enclosure controlled by only one density monitor (pipe between poles could create SF6 gas flow). Such a type of configuration could reduce the number of alarms but without improving SF6 tightness and the repair would not be made easier.

Table 4.4.5 : SF6 tightness failures per voltage and for different enclosure technologies
Major and minor failures

Voltage (kV)	Metal enclosed			Non metal enclosed			Ratio failure rate ME / NME
	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years	
All voltages	30400	165	0.54	40308	1148	2.85	0.19
63 ≤ V < 100	16186	62	0.38	8169	149	1.82	0.21
100 ≤ V < 200	7426	64	0.86	16094	330	2.05	0.42
200 ≤ V < 300	1450	11	0.76	9483	392	4.13	0.18
300 ≤ V < 500	4099	22	0.54	5818	258	4.43	0.12
500 ≤ V < 700 1)	1236	6	0.48	659	15	2.28	0.21
700 ≤ V 1)	3	0	0.00	85	4	4.70	0.00

1) Results not significant due to the small numbers
of failures or of sample size

cb = circuit-breaker
ME = Metal enclosed
NME = Non metal enclosed

Table 4.4.6 : SF6 tightness failures per voltage and for different locations
Major and minor failures

Voltage (kV)	Indoor			Outdoor		
	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years
All voltages	10500	86	0.82	60208	1227	2.04
63 ≤ V < 100	4266	41	0.96	20089	170	0.85
100 ≤ V < 200	3946	37	0.94	19574	357	1.82
200 ≤ V < 300 1)	399	1	0.25	10534	402	3.82
300 ≤ V < 500 1)	1647	1	0.06	8270	279	3.37
500 ≤ V < 700	242	6	2.48	1653	15	0.91
700 ≤ V	0	0	0.00	88	4	4.55

1) Results for indoor circuit-breakers not significant due to
the small number of failures

cb = circuit-breaker

Table 4.4.7 : SF6 tightness failures per voltage and for different ages of the circuit-breakers
Major and minor failures

Voltage (kV)	Placed in service before 1.1.83			Placed in service after 1.1.83		
	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years
All voltages	21157	537	2.54	49551	776	1.57
63 ≤ V < 100	7057	50	0.71	17298	161	0.93
100 ≤ V < 200	6365	174	2.73	17155	220	1.28
200 ≤ V < 300	3515	166	4.72	7418	237	3.19
300 ≤ V < 500	3462	140	4.04	6455	140	2.17
500 ≤ V < 700	755	7	0.93	1140	14	1.23
700 ≤ V	3	0	0.00	85	4	4.70

cb = circuit-breaker

4.4.4 Comparison of tightness relevant to metal enclosed and non metal enclosed circuit-breaker

Table 4.4.8 shows distribution of SF6 tightness failures according to enclosure technology of the circuit-breaker. In first analysis, tightness failures of non metal enclosed circuit-breakers are five times higher than those for metal enclosed ones. Before concluding, the results of type of enclosure correlated with the other parameters must be analysed.

Table 4.4.5 presents results of enclosure technology correlated with voltage. For all classes of voltage, metal enclosed circuit-breakers have a better tightness than non metal enclosed circuit-breakers. Table 4.4.9 shows results of enclosure technology correlated with location. Table 4.4.10 presents results of enclosure technology correlated with age.

These results indicate that for metal enclosed outdoor circuit-breaker, SF6 tightness is much better than for the non metal enclosed type. About indoor location, the comparison between metal enclosed

Table 4.4.8 : SF6 tightness failures according to enclosure technology
Major and minor failures

Envelope technology	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years
Metal enclosed	30400	165	0.54
Non metal enclosed	40308	1148	2.85
Total	70708	1313	1.86

cb = circuit-breaker

and non metal enclosed circuit-breakers is not significant given the large difference in the circuit-breaker population considered. These results must be considered with great care, as has been shown in chapter 2.11 and 5.

Table 4.4.9 : SF6 tightness failures per location and for different enclosure technologies
Major and minor failures

Location of circuit-breaker	Metal enclosed			Non metal enclosed			Ratio failure rate ME / NME
	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years	
Indoor	8026	74	0.92	2474	13	0.53	0.57
Outdoor	22374	91	0.41	37834	1135	3.00	7.38
Total	30400	165	0.54	40308	1148	2.85	5.25

cb = circuit-breaker
ME = Metal enclosed
NME = Non metal enclosed

Table 4.4.10 : SF6 tightness failures per age and for different enclosure technologies
Major and minor failures

Circuit-breaker placed in service	Metal enclosed			Non metal enclosed			Ratio failure rate ME / NME
	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years	
before 1.1.83	10768	59	0.55	10389	478	4.60	8.40
after 1.1.83	19632	106	0.54	29919	670	2.24	4.15
Total	30400	165	0.54	40308	1148	2.85	5.25

cb = circuit-breaker ME = Metal enclosed
NME = Non metal enclosed

4.4.5 Correlation concerning SF6 tightness and location (indoor, outdoor)

Table 4.4.11 presents the results of SF6 tightness according to the location of circuit-breaker, indoor or outdoor. The first remark is that outdoor population is 6 times more numerous than indoor population of circuit-breaker. The second remark is that SF6 tightness of indoor circuit-breakers is 2.5 times better than tightness of outdoor circuit-breakers. For more explanation Table 4.4.6 presents location correlated with voltage, Table 4.4.9 location correlated with enclosure technology and the Table 4.4.12 location correlated with age. SF6 tightness is better for indoor installation than for outdoor installation. The protection against rain and different environmental aggressions explains the better behaviour of indoor equipment.

Table 4.4.11 : SF6 tightness failures according to location
Major and minor failures

Location of circuit-breaker	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years
Indoor	10500	87	0.83
Outdoor	60208	1226	2.04
Total	70708	1313	1.86

cb = circuit-breaker

Table 4.4.12 : SF6 tightness failures per age and for different locations
Major and minor failures

Circuit-breaker placed in service	Indoor			Outdoor		
	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years
before 1.1.83	3929	15	0.38	17228	522	3.03
after 1.1.83	6571	72	1.10	42980	704	1.64
Total	10500	87	0.83	60208	1226	2.04

cb = circuit-breaker

4.4.6 Correlation concerning SF6 tightness and age of circuit-breaker

Table 4.4.13 presents failures of SF6 tightness for circuit-breakers placed in service before and after 1983. Globally the results of circuit-breakers placed in service after 1983 are better than the results of the previous circuit-breakers. The progress in design and manufacture of circuit-breakers can be an explanation of these results. But leakage can appear long time after commissioning and the effect of age can also be a factor for the higher failure of breakers placed in service before 1983.

Table 4.4.7 presents results of age correlated with voltage, Table 4.4.10 age correlated with enclosure technology, Table 4.4.12 age correlated with location. These results show that age has an influence especially for outdoor non metal enclosed circuit-breakers.

Table 4.4.13 : SF6 tightness failures according to age
Major and minor failures

Circuit-breaker placed in service	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-years
before 1.1.83	21157	537	2.54
after 1.1.83	49551	776	1.57
Total	70708	1313	1.86

cb = circuit-breaker

4.4.7 Components concerned by failure of SF6 tightness

Table 4.4.14 gives the localization of SF6 leakage, that is to say the component concerned. As it can be seen, minor failures of SF6 tightness concern essentially components at service voltage, that is to say mainly breaker-units and isolation; then it is electrical control and more precisely density monitor. Both, *components at service voltage* and *density monitor*, represent 87 % of SF6 tightness failures.

4.4.8 Characteristics of SF6 tightness failures

According to Table 4.4.15 about characteristics of the minor failure, the anomalies of tightness are due to corrosion in about 40 % of cases and about 60 % due to other causes as those mentioned in

Table 4.4.14 : Component responsible for SF6 tightness minor failures

Component responsible for SF6 tightness minor failures	Number of failures	Percentage %
Component at service voltage	907	73.4
Electrical control & aux. circuits:		
-density monitor	176	14.2
-other control & aux. components	6	0.5
Operating mechanism	62	5.0
Others	85	6.9
Total	1236	100.0

paragraph 4.2.2. This result can be questioned as the population of circuit-breakers is relatively young; the oldest circuit-breakers of this enquiry being 14 years old (placed in service after 1978). The defect due to corrosion is more complicated to repair than those due to other causes, like a pinched seal or impurity under seal.

Table 4.4.15 : Characteristics of SF6 tightness minor failures

Characteristics of small SF6 leakage	Number of failures	Percentage %
Small SF6 leakage due to corrosion	528	40.7
Small SF6 leakage due to other causes	769	59.3
Total	1297	100.0

4.5 The results of SF6 supervision monitor

4.5.1 Results concerning major and minor failure of density monitor

The failures of density monitors represent 4 % of major failures and 11 % of minor failures. The major failures are mainly due to locking of circuit-breaker in close or open position (see Table 4.4.3).

4.5.2 Analysis of density monitor failures

Table 4.4.16 presents the origins of density monitor failures and more exactly the correlation between the monitor failures and the part of the breaker to which the failure is related. In the case of density monitor, SF6 tightness is the main origin of the failures (181 failures or about half of total). The consequences of density monitor due to tightness are relatively limited: only 5 major failures of density monitor are due to SF6 tightness.

Defect of electrical auxiliary control circuit is the second origin of density monitor failures, but the consequences are more serious because the reduction of dielectric withstand of circuit-breaker could not be signalled.

4.5.3 Analysis of the causes

Table 4.4.17 precises the causes of density monitor failures. The main cause of density monitor failure is due to manufacture.

4.6 Overall SF6 tightness failure rates

Tables 4.6.1 and 4.6.2 give the failures and failure rates for all failures whose origin is tightness of SF6. Distinction is made between indoor/outdoor and metal enclosed/non metal enclosed.

Table 4.4.16 : Origin of SF6 density monitor failures

Origin of SF6 density monitor failures	Density monitor major failures		Density monitor minor failures		Total	
	Number of failures	Percentage †	Number of failures	Percentage †	Number of failures	Percentage †
Mechanical in operating mechanism (earthed)	3	15.8	43	12.7	46	12.9
Mechanical in other parts of circuit-breaker	5	26.3	58	17.2	63	17.6
Electrical (main circuit)	0	0.0	0	0.0	0	0.0
Electrical (auxiliary and control circuit)	6	31.6	61	18.0	67	18.8
Tightness of SF6 gas system	5	26.3	176	52.4	181	50.7
Total	19	100.0	338	100.0	357	100.0

Table 4.4.17 : Causes of SF6 density monitor failures

Cause of SF6 density monitor failures	Density monitor major failures		Density monitor minor failures		Total	
	Number of failures	Percentage †	Number of failures	Percentage †	Number of failures	Percentage †
Design	1	5.9	39	11.3	40	11.1
Manufacture	10	58.8	169	49.1	179	49.6
Inadequate instruction (erect. oper. maint.)	0	0.0	1	0.3	1	0.3
Incorrect erection	4	23.5	21	6.1	25	6.9
Incorrect operation	0	0.0	59	17.2	59	16.3
Incorrect maintenance	1	5.9	4	1.2	5	1.4
Stresses beyond those specified	0	0.0	4	1.2	4	1.1
Other external causes	0	0.0	26	7.6	26	7.2
Other	1	5.9	21	6.0	22	6.1
Total	17	100.0	344	100.0	361	100.0

Table 4.6.1 : Rates of major failures whose origin is tightness of SF6

Voltage (kV)	Location Indoors						Location Outdoors					
	Metal enclosed			Non metal enclosed			Metal enclosed			Non metal enclosed		
	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-year	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-year	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-year	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-year
All voltages	8026	0	0.00	2474	1	0.04	22374	3	0.01	37834	29	0.08
63 ≤ V < 100	2781	0	0.00	1485	0	0.00	13405	0	0.00	6684	1	0.01
100 ≤ V < 200	3474	0	0.00	472	0	0.00	3952	3	0.08	15622	7	0.04
200 ≤ V < 300	264	0	0.00	135	1	0.74	1186	0	0.00	9348	8	0.09
300 ≤ V < 500	1274	0	0.00	373	0	0.00	2825	0	0.00	5445	10	0.18
500 ≤ V < 700	233	0	0.00	9	0	0.00	1003	0	0.00	650	1	0.15
700 ≤ V	0	0	0.00	0	0	0.00	3	0	0.00	85	2	2.35

cb = circuit-breaker

Table 4.6.2 : Rates of minor failures whose origin is tightness of SF6

Voltage (kV)	Location Indoors						Location Outdoors					
	Metal enclosed			Non metal enclosed			Metal enclosed			Non metal enclosed		
	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-year	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-year	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-year	Sample size (cb-years)	Number of SF6 tightness failures	Failures per 100 cb-year
All voltages	8026	74	0.92	2474	11	0.44	22374	88	0.39	37834	1106	2.92
63 ≤ V < 100	2781	34	1.22	1485	7	0.47	13405	28	0.21	6684	141	2.11
100 ≤ V < 200	3474	34	0.98	472	3	0.64	3952	27	0.68	15622	320	2.05
200 ≤ V < 300	264	0	0.00	135	0	0.00	1186	11	0.93	9348	383	4.10
300 ≤ V < 500	1274	0	0.00	373	1	0.27	2825	22	0.78	5445	247	4.54
500 ≤ V < 700	233	6	2.58	9	0	0.00	1003	0	0.00	650	14	2.15
700 ≤ V	0	0	0.00	0	0	0.00	3	0	0.00	85	1	1.18

cb = circuit-breaker

4.7 Conclusions

Two origins of failures mainly stand out in relief from the results of the Second International Enquiry on single pressure SF6 circuit-breaker failures and defects in service. The first concerns mechanical problems in operating system (40% of all failures). The second concerns the SF6 tightness (36% of all failures).

The failures of SF6 tightness represent only 7% of major failures. It is the lowest rate for all the origins of the enquiry. The explanation for this good result is that tightness is monitored on-line and a warning can be given to the operator before emergence of a major failure: but this involves minor failures. On the other hand, SF6 tightness represents 40% of the origins of minor failures: it is the highest rate among all the origins of minor failures.

The data about SF6 tightness could have been more numerous if the definition of tightness failure had been the same for all the countries of the enquiry: some countries have reported a failure at each SF6 alarm, others only after having repaired the circuit-breaker and for others only when the frequency of alarms was increasing. In any case, the analysis of data concerning failures related to SF6 tightness supports the following statements:

- * The rate of failures having tightness of SF6 gas system as origin is on average of 1.86 failures per 100 circuit-breaker-years; this parameter, evaluated on the basis of different circuit-breaker populations selected according to different circuit-breaker characteristics as type of enclosure, type

or date of placed in service, falls in a range with a ratio of 12 between extreme values.

- * The tightness of circuit-breakers belonging to the lowest range of voltage is in general better than the others.
- * The type of installation (indoor, outdoor) and the age of service do not seem to affect substantially the reliability of the circuit-breaker tightness for metal enclosed circuit-breakers while it seems important for the non metal enclosed ones: the failure rate of non metal enclosed circuit-breakers placed in service before 1983 is twice the corresponding one relevant to the newer circuit-breakers. Circuit-breakers installed outdoor have a failure rate about 2.5 times higher than the corresponding ones relevant to the indoor types.
- * Design and manufacture are the main causes of the tightness failures and locking or automatic opening represents the main characteristics of the major failures.
- * The SF6 circuit breaker tightness is monitored continuously by a density monitor. This component plays a decisive role for the guarantee of the functional characteristics of the breaker. The results of the enquiry show that the failures of the monitoring device concern the tightness and the electrical auxiliary control circuits and are mainly due to manufacture.

Some progress must be done by the manufacturers for future circuit-breakers in the tightness field and for density monitor reliability, which is an important component allowing to check the dielectric integrity of the circuit-breakers.

5. ANALYSIS OF THE COLLECTED DATA WITH REFERENCE TO THE TYPE OF CIRCUIT-BREAKER ENCLOSURE

5.1 Introduction

This chapter forms part of a CIGRE Technical Brochure. In conjunction with the introduction to this brochure it can be read as a separate document.

The total number of circuit-breaker-years, the circuit-breaker population, on which the following study is based, comprises 70708 single pressure SF6 circuit-breaker-years in the voltage range of 63 kV up to 700 kV and above. The data was received from 132 utilities of 22 countries which answered the CIGRE questionnaire of the Second International Enquiry on single pressure SF6 circuit-breaker failures and defects in service during the years 1988-1991. The circuit-breakers were described by their rated voltage, the year of installation, the type of location, the type of enclosure and the type of operating mechanism. Each failure was identified by the circuit-breaker component and the stress responsible for it and classified according to a list of suggested failure modes, origins and causes. In addition, information on the consequences of the major failures in terms of circuit-breaker downtime, the time required to obtain spare parts and the existence of a fire and/or explosion of the circuit-breaker was also provided.

In the present report the type of the circuit-breaker enclosure, i.e. metal enclosed (ME) or non metal enclosed (NME) has been taken as the main parameter of investigation and the analysis of the data has been mainly performed with the purpose of providing information on the failure distribution and its correlations with the other describing parameters.

The evaluation of the possible impact of the type of enclosure on the reliability of the circuit-breakers is also an objective of this study. The reliability definitions as major failure (MF), minor failure (mf), circuit-breaker downtime, overhauls and others used in the text are assumed known as given in [8].

In the following information on the characteristics of the investigated circuit-breakers, their scheduled overhauls, the failure rate, the origin, cause and characteristics of the failure, the identification of the component responsible for the failure, the circuit-breaker downtime and the time to obtain spare parts is given.

5.2 General Information

Circuit-breaker population:

The total number of circuit-breakers considered over the four years of the Second International Enquiry is, as already mentioned above, 70708, 43% of which are metal enclosed (ME) and 57% non metal enclosed (NME).

- 35.4% of the ME circuit-breakers and 25.8% of the NME type were installed before 1983.
- 73.6% of the ME circuit-breakers and 93.9% of the NME type are outdoor located.
- 43.2% of the ME circuit-breakers are pneumatically operated, 33.7% hydraulically and 23.1% spring operated.
- 64.8% of the NME circuit-breakers are hydraulically operated, 20.1 % pneumatically and 15.0% spring operated.

Fig. 5.2.1 and Fig. 5.2.2 show the distribution of the circuit-breaker population among the participating countries for ME and NME types respectively. From them it comes out that one single country sums up 75% of the whole ME circuit-breaker population and another country represents 37% of the NME circuit-breaker population. It has to be noted that the order of countries is not identical for Fig. 5.2.1 and 5.2.2.

Estimated average interval between scheduled overhauls:

Disregarding the data concerning the circuit-breakers rated 700 kV and above for which a few data are available, the average interval between scheduled overhauls is in the range 6 to 9 years, the ME type presenting a slight longer interval. See Table 5.2.1.

Estimated average labour effort for scheduled overhaul:

On average a scheduled overhaul requires 18 man hours per circuit-breaker per year; no practical difference between ME and NME circuit-breakers seems appreciable. See Table 5.2.2.

Estimated average cost of spare parts consumed for scheduled overhaul:

On average the cost of spare parts for a scheduled overhaul of the ME circuit-breakers is 40 man hours per circuit-breaker per year and it results at least three times higher than the corresponding one for NME types. See Table 5.2.3.

5.3 Failures and defects

Failure rates:

Considering the distribution of the circuit-breaker population given in Fig. 5.2.1 and Fig. 5.2.2 the circuit-breaker failure rates have been basically calculated both on the whole set of circuit-breakers and on the set resulting from the exclusion of the two countries having the highest and lowest population (given in brackets in the following).

Table 5.3.1 reports the failure rates calculated also on different sets of circuit-breakers and associated failures chosen on the basis of the different circuit-breaker characteristics.

From it the following considerations come out:

Major failures:

On the whole NME circuit-breakers show a failure rate of 0.94 (0.98) failures per 100 circuit-breaker years and the ME types 0.32 (1.04) failures per 100 circuit-breaker years. Different values can be associated to other circuit-breaker sub-sets as shown in Table 5.3.1.

The type of installation seems to affect the failure rate mainly in the case of the NME circuit-breakers which present 1.0 (1.01) failures per 100 circuit-breaker years if outdoor installed and 0.08 (0.14) if indoor installed. The corresponding values in the case of ME circuit-breakers are 0.25 (1.66) failures per 100 circuit-breaker years and 0.52 (0.73) failures per 100 circuit-breaker years, respectively.

The date of installation does not generally seem of practical interest, the failure rate being 0.86 (0.98) failures per 100 circuit-breaker years and 0.97 (0.98) failures per 100 circuit-breaker years for the NME circuit-breakers placed in service before and after 1983,

respectively. The corresponding values for ME circuit-breakers are 0.28 (0.79) failures per 100 circuit-breaker years and 0.34 (1.18) failures per 100 circuit-breaker years, respectively.

The type of operating mechanism does not seem to introduce a decisive and stable tendency on the behaviour of the circuit-breakers, the values of the failure rate being 0.83 (0.84), 1.07 (1.13) and 1.17 (1.42) failures per 100 circuit-breaker years for NME circuit-breakers hydraulically, spring and pneumatically operated, respectively. For the ME circuit-breakers values of 0.16 (0.59), 0.29 (1.51) and 0.48 (0.98) failures per 100 circuit-breaker years are associated with the spring, pneumatic and hydraulic mechanism. When comparing the impact of the type of operating mechanism on the circuit-breaker failure rate it should be considered that most of the spring mechanism operate circuit-breakers rated below 200 kV.

Circuit-breakers rated 100 kV and below present a decisive lower failure rate, both for ME and NME types.

Minor failures:

On the whole NME circuit-breakers show a failure rate of 6.69 (6.99) failures per 100 circuit-breaker years and the ME types 2.18 (6.44) failures per 100 circuit-breaker years. Different values can be associated to other circuit-breaker sub-sets as shown in Table 5.3.1.

The type of installation seems to affect the failure rate mainly in the case of the NME circuit-breakers which present 7.08 (7.2) failures per 100 circuit-breaker years if outdoor installed and 0.77 (1.29) if indoor installed. The corresponding values in the case of ME circuit-breakers are 1.54 (7.19) failures per 100 circuit-breaker years and 3.95 (6.06) failures per 100 circuit-breaker years, respectively.

The date of installation does not generally seem of practical interest, the failure rate being 8.4 (9.47) failures per 100 circuit-breaker years and 6.09 (6.21) failures per 100 circuit-breaker years for the NME circuit-breakers placed in service before and after 1983, respectively. The corresponding values for ME circuit-breakers are 2.41 (7.01) failures per 100 circuit-breaker years and 2.05 (6.12) failures per 100 circuit-breaker years, respectively.

The type of operating mechanism seems to introduce

a tendency on the behaviour of the circuit-breakers, the values of the failure rate being 3.28 (3.39), 4.15 (5.0), 8.27 (8.29) failures per 100 circuit-breaker years when considering NME circuit-breakers spring, pneumatically and hydraulically operated, respectively. The corresponding values for the ME circuit-breakers are 0.46 (0.76), 1.13 (3.46) and 4.7 (9.23) failures per 100 circuit-breaker years, respectively.

When comparing the impact of the type of operating mechanism on the circuit-breaker failure rate it should be considered that most of the spring mechanism operate circuit-breakers rated below 200 kV.

Circuit-breakers rated 100 kV and below present a decisive lower failure rate, both for ME and NME types.

Origin of the failure:

Table 5.3.2 shows that for major failures mechanical origin is the most recurrent, taking 55% of the cases. The electrical origin is also important, concerning about 40% of the cases. As for minor failures Table 5.3.3 shows that mechanical origin takes 60% in the case of ME circuit-breakers and on average 46% in the case of NME types.

SF₆ tightness remains the other important origin of the defects, with a percentage of 25% and 43%, respectively. For the older NME circuit-breakers tightness of SF₆ is the major cause of failure, concerning 55% of the cases.

Electrical main circuit origin remains below 15% in all cases.

Cause of the failure:

Table 5.3.4 shows that more than 50% of the major failure causes are concerned with *design* or *manufacture*. The causes more relevant to the service as the *incorrect erection*, the *incorrect operation* and *incorrect maintenance* concern about 17% of the cases. The type of enclosure does not seem to play a particular role.

As for minor failures *design* and *manufacture* represent 61% of the cases for ME circuit-breakers and 65% for NME ones, as shown in Table 5.3.5.

Incorrect erection, incorrect operation or *incorrect maintenance* concern about 10% of the cases for ME circuit-breakers and 15% for NME ones; *manufacture* seems a slightly more important cause than *design* for the newer circuit-breakers.

Characteristics of the failure:

As for the major failures there is practically a similar distribution among most of the characteristics listed in Table 5.3.6 for ME and NME circuit-breakers.

For any type of circuit-breaker the item *locking in open or closed position* and *does not close on command* are the most recurrent, the first adding up a 28% both for ME and NME circuit-breakers and the latter a 20% and 26% for ME and NME, respectively.

For minor failures the leakages in the operating mechanism play the major role both for NME and ME circuit-breakers, taking a 29-37% of the cases, as shown in Table 5.3.7. SF₆ leakages result more frequent for NME circuit-breakers adding up a 42%.

Identification of the sub-assembly or component responsible for the failure:

For both ME and NME circuit-breakers the major responsibility for the major failures is identified in the operating mechanism which takes more than 40% of the cases, Table 5.3.8; the electrical control and auxiliary circuits are responsible for a 25-30% of the cases while about 20-27% is declared under the item *component at service voltage*.

As for minor failures the three main items reported in Table 5.3.9 i.e. the *component at service voltage*, the *electrical control and auxiliary circuits* and the *operating mechanism* share some 20%, 17%, 55% and 34%, 20%, 41% for ME and NME circuit-breakers, respectively.

5.4 Conclusions

Considering the impact of the type of the circuit-breaker enclosure, i.e. metal enclosed (ME) and non metal enclosed (NME), on the failures the following conclusions can be drawn:

* On average both a ME or a NME circuit-breaker is overhauled every 7 to 8 years, each overhaul

requiring 18 man hours of labour effort. The average cost of spare parts consumed for a scheduled overhaul is 40 man hours for a ME circuit-breaker and 12 man hours for a NME one.

- * Different values of the failure rate can be taken as representative of the ME or NME circuit-breakers according to the specific set taken as a reference.

In general NME circuit-breakers show a failure rate of about three times that of the ME types, respectively of 0.94 failures per 100 circuit-breaker years and 0.32 failures per 100 circuit-breaker years for the major failures and 6.7 failures per 100 circuit-breaker years and 2.2 failures per 100 circuit-breaker years for the minor failures.

NME outdoor installed circuit-breakers present a failure rate much higher than that of the indoor type, respectively of 1 failure per 100 circuit-breaker years and 0.08 failures per 100 circuit-breaker years for the major failures and 7.1 failures per 100 circuit-breaker years and 0.77 failures per 100 circuit-breaker years for the minor failures.

- * This situation concerning the circuit-breaker failure rate substantially changes when the set of the circuit-breakers taken as a reference for calculations excludes the population of the two countries having declared respectively the highest and the lowest number of circuit-breakers. In this case in general no practical difference appears between ME and NME failure rates which result respectively of 1.04 failures per 100 circuit-breaker years and 0.98 failures per 100 circuit-breaker years for major failures and 6.44 failures per 100 circuit-breaker years and 6.99 failures per 100 circuit-breaker years for minor failures.

Still the substantial difference between the NME outdoor installed circuit-breakers and the indoor type is confirmed.

- * For both ME and NME circuit-breakers the mechanical origin is the most important one, adding up some 55% of the cases for major failures and respectively 60% and 46% for minor failures. Electrical origin is also important for major failures, concerning about 40% of the cases while for minor failures SF₆ tightness is the other prevailing origin with its 25% and 43% for ME and NME circuit-breakers, respectively.

- * *Design and manufacture* represent more than 50% of the causes of failure for both ME and NME circuit-breakers. *Incorrect erection, incorrect operation and incorrect maintenance* cause about 17% of the major failures and 10% and 15% of the minor failures, respectively for ME and NME circuit-breakers.

- * As for the characteristics of the major failures, the circuit-breakers are declared mainly to remain *locked in open or closed position*, for a 28% of the cases, or *not to close on command*, for a 20% or a 26%, respectively for ME and NME circuit-breakers. For minor failures leakage in operating mechanism adds up a 37% in the case of ME circuit-breakers and a 29% for the NME ones. SF₆ leakages in ME circuit-breakers represent a 29% and a 42%, respectively for ME and NME circuit-breakers;

- * For both ME and NME circuit-breakers the major responsibility for the major failures is identified in the *operating mechanism*, for a 43% of the cases. *Electrical control and auxiliary circuits* are responsible for about a 25-30% of the major failures while about 27% and 19% of them involve *components at service voltage*, respectively for ME and NME circuit-breakers. As for the minor failures the three main responsible sub-assemblies identified, i.e. the *component at service voltage*, the *electrical control and auxiliary circuits* and the *operating mechanism*, share some 20%, 17%, 55% and 34%, 20%, 41% respectively for ME and NME circuit-breakers.

5.5 References

- [8] A.L.J. Janssen, W. Degen, M. Tudrej, S. Ikeda
Application of Diagnostic Techniques for High Voltage Circuit-Breakers.
CIGRE Session 1992, 13-101

Fig. 5.2.1 : Number of circuit-breakers per country
Metal enclosed

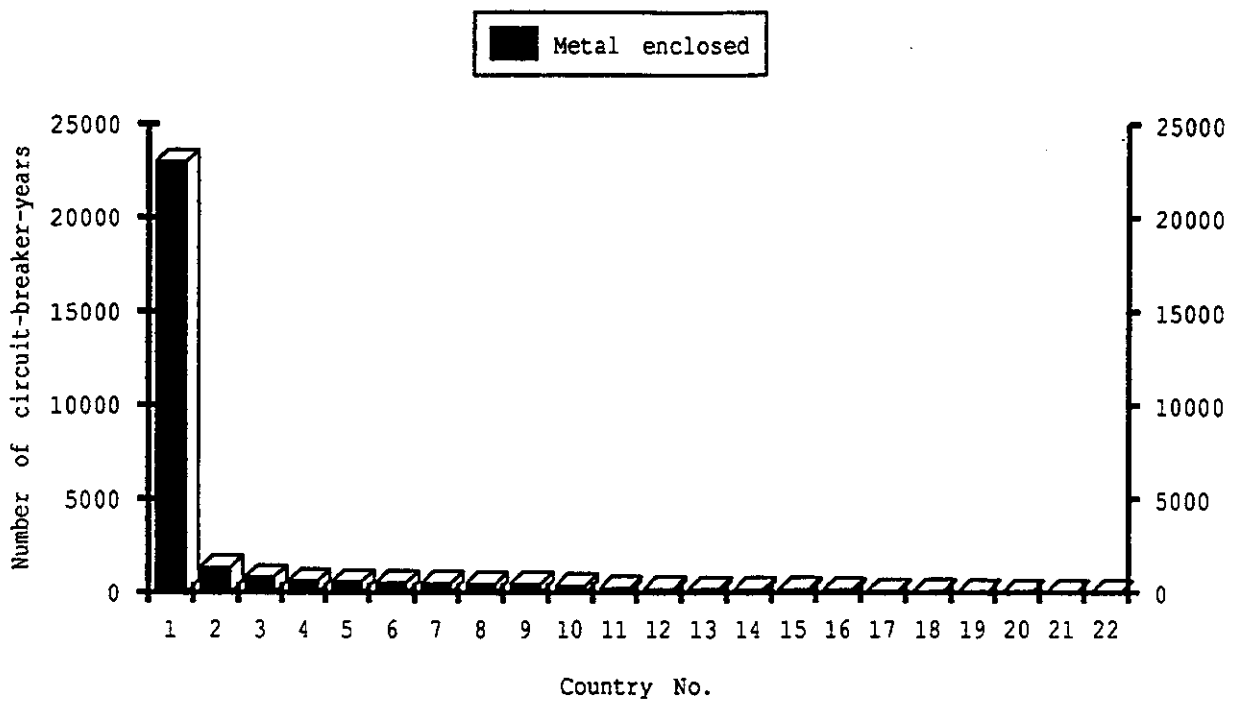


Fig. 5.2.2 : Number of circuit-breakers per country
Non metal enclosed

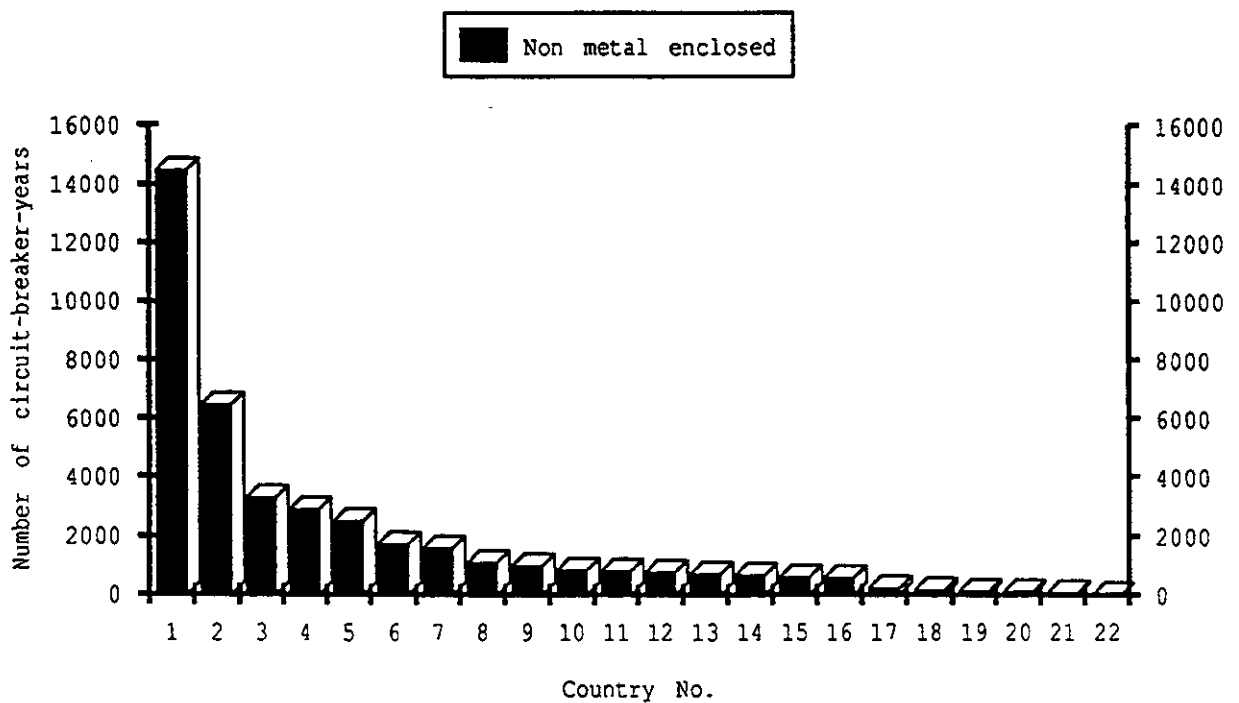


Table 5.2.1 : Average interval between scheduled overhauls (years)

Voltage (kV)	Metal enclosed										Non metal enclosed					
	Type of operating mechanism					Total					Type of operating mechanism			Total		
	A		B		C		B		C		A		B		C	
	Average interval (years)	Number of answers	Average interval (years)	Number of answers	Average interval (years)	Number of answers	Average interval (years)	Number of answers	Average interval (years)	Number of answers	Average interval (years)	Number of answers	Average interval (years)	Number of answers	Average interval (years)	Number of answers
All voltages	8.5	362	7.3	242	8.6	172	8.1	776	7.0	527	7.4	444	7.1	369	7.1	1340
63 ≤ V < 100	7.6	49	7.5	45	7.1	50	7.4	144	7.8	29	6.2	66	6.7	69	6.7	164
100 ≤ V < 200	8.6	137	7.3	92	9.6	101	8.5	330	6.8	217	7.6	168	7.2	202	7.2	587
200 ≤ V < 300	8.3	42	6.8	31	5.3	8	7.4	81	7.5	123	8.2	95	7.6	54	7.7	272
300 ≤ V < 500	8.2	94	7.2	52	8.9	13	7.9	159	6.5	116	6.5	91	6.9	42	6.6	249
500 ≤ V < 700	9.2	37	7.8	22	0.0	0	8.7	59	6.6	36	8.8	21	4.0	2	7.3	59
700 ≤ V	20.0	3	0.0	0	0.0	0	20.0	3	11.0	6	12.0	3	0.0	0	11.3	9

A: Hydraulic mechanism, which may include spring

B: Pneumatic mechanism, which may include spring

C: Spring operated mechanism

Table 5.2.2 : Estimated average labour effort for scheduled overhaul
Mean values on the whole circuit-breaker population (man hours / year / circuit-breaker)

Voltage (kV)	Metal enclosed										Non metal enclosed									
	Type of operating mechanism					Total					Type of operating mechanism					Total				
	A	B	C	Total	Average labour effort (man hours/year/cb)	Number of answers	Average labour effort (man hours/year/cb)	Number of answers	Average labour effort (man hours/year/cb)	Number of answers	Average labour effort (man hours/year/cb)	Number of answers	Average labour effort (man hours/year/cb)	Number of answers	Average labour effort (man hours/year/cb)	Number of answers	Average labour effort (man hours/year/cb)	Number of answers		
All voltages	18.2	362	21.4	242	12.3	172	17.9	776	19.6	529	23.0	444	9.3	369	17.9	1342				

A: Hydraulic mechanism, which may include spring
 B: Pneumatic mechanism, which may include spring
 C: Spring operated mechanism
 cb = circuit-breaker

Table 5.2.3 : Estimated average cost of spare parts consumed for scheduled overhaul
Mean values on the whole circuit-breaker population (man hours / year / circuit-breaker)

Voltage (kV)	Metal enclosed										Non metal enclosed									
	Type of operating mechanism					Total					Type of operating mechanism					Total				
	A	B	C	Total	Average cost of spare parts (man hours/year/cb)	Number of answers	Average cost of spare parts (man hours/year/cb)	Number of answers	Average cost of spare parts (man hours/year/cb)	Number of answers	Average cost of spare parts (man hours/year/cb)	Number of answers	Average cost of spare parts (man hours/year/cb)	Number of answers	Average cost of spare parts (man hours/year/cb)	Number of answers	Average cost of spare parts (man hours/year/cb)	Number of answers		
All voltages	39.0	362	49.8	242	29.1	172	40.2	776	12.2	529	15.5	444	6.7	369	11.8	1342				

A: Hydraulic mechanism, which may include spring
 B: Pneumatic mechanism, which may include spring
 C: Spring operated mechanism
 cb = circuit-breaker

Table 5.3.1 : Failure rates evaluated for different sets of circuit-breakers and associated failures

Circuit-breaker characteristic	Circuit-breaker population		Major failure rate		Minor failure rate	
	Sample size (cb-years)	Sample size (cb-years)	Failures per 100 cb-years	Failures per 100 cb-years	Failures per 100 cb-years	Failures per 100 cb-years
	All countries	All countries minus two extremes 1)	All countries	All countries minus two extremes 1)	All countries	All countries minus two extremes 1)
All breakers	70708	45907	0.67	1.00	4.75	6.90
Metal enclosed	30400	7410	0.32	1.04	2.18	6.44
Non metal enclosed	40308	38497	0.94	0.98	6.69	6.99
Metal enclosed indoor installed cb	8026	4935	0.52	0.73	3.95	6.06
Metal enclosed outdoor installed cb	22374	2475	0.25	1.66	1.54	7.19
Non metal enclosed indoor installed cb	2474	1399	0.08	0.14	0.77	1.29
Non metal enclosed outdoor installed cb	37834	37098	1.00	1.01	7.08	7.20
Metal enclosed installed before 1.1.83	10768	2668	0.28	0.79	2.41	7.01
Metal enclosed installed after 1.1.83	19632	4742	0.34	1.18	2.05	6.12
Non metal encl. installed before 1.1.83	10389	9194	0.86	0.98	8.40	9.47
Non metal encl. installed after 1.1.83	29919	29303	0.97	0.98	6.09	6.21
Metal enclosed with hydraulic mechanism	10258	4378	0.48	0.96	4.70	9.23
Metal enclosed with pneumatic mechanism	13138	1850	0.29	1.51	1.13	3.46
Metal enclosed with spring mechanism	7004	1182	0.16	0.59	0.46	0.76
Non metal enclosed with hydr. mechanism	26124	26044	0.83	0.84	8.27	8.29
Non metal enclosed with pneum. mechanism	8120	6708	1.17	1.42	4.15	5.00
Non metal enclosed with spring mechanism	6064	5745	1.07	1.13	3.28	3.39
Metal enclosed rated below 100 kV	16186	2)	0.07	2)	0.90	2)
Metal enclosed rated 100 kV & above	14214	2)	0.61	2)	3.64	2)
Non metal enclosed rated below 100 kV	8169	2)	0.69	2)	4.86	2)
Non metal enclosed rated 100 kV & above	32139	2)	1.00	2)	7.15	2)

1) All countries excluded those having the two extreme circuit-breaker populations (lowest and highest)

2) Not evaluated

cb = circuit-breaker

Table 5.3.2 : Origin of major failures

	Metal enclosed				Non metal enclosed					
	Placed in service 1.1.78 - 1.1.83		Placed in service after 1.1.83		Placed in service 1.1.78 - 1.1.83		Placed in service after 1.1.83			
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers		
Mechanical in operating mechanism (earthed)	31.0	9	53.2	33	30.2	26	47.5	135	43.5	161
Mechanical in other parts of circuit-breaker	10.3	3	8.1	5	16.3	14	9.2	26	10.8	40
Electrical (main circuit)	20.7	6	22.6	14	9.3	8	12.7	36	11.9	44
Electrical (auxiliary and control circuit)	34.5	10	12.9	8	27.9	24	25.0	71	25.7	95
Tightness of SF6 gas system	3.4	1	3.2	2	16.3	14	5.6	16	8.1	30
Total number of received answers		29		62		86		284		370
		1)		2)		4)		5)		6)

1) Equal to 96.6% of MF of all the countries

2) Equal to 92.5% of MF of all the countries

3) Equal to 93.8% of MF of all the countries

4) Equal to 96.6% of MF of all the countries

5) Equal to 98.3% of MF of all the countries

6) Equal to 97.3% of MF of all the countries

MF = major failure

Table 5.3.3 : Origin of minor failures

	Metal enclosed						Non metal enclosed					
	Placed in service 1.1.78 - 1.1.83		Placed in service after 1.1.83		All period		Placed in service 1.1.78 - 1.1.83		Placed in service after 1.1.83		All period	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers
Mechanical in operating mechanism (earthed)	50.2	128	51.0	202	50.7	330	26.5	222	41.5	723	36.6	945
Mechanical in other parts of circuit-breaker	11.0	28	11.1	44	11.1	72	9.2	77	9.7	170	9.6	247
Electrical (main circuit)	1.2	3	1.8	7	1.5	10	1.0	8	0.6	11	0.7	19
Electrical (auxiliary and control circuit)	14.9	38	9.8	39	11.8	77	8.0	67	10.7	186	9.8	253
Tightness of SF6 gas system	22.7	58	26.3	104	24.9	162	55.4	464	37.5	654	43.3	1118
Total number of received answers		255		396		651		838		1744		2582
		1)		2)		3)		4)		5)		6)

1) Equal to 98.4% of mf of all the countries

2) Equal to 98.3% of mf of all the countries

3) Equal to 98.3% of mf of all the countries

4) Equal to 95.9% of mf of all the countries

5) Equal to 95.6% of mf of all the countries

6) Equal to 95.8% of mf of all the countries

mf = minor failure

Table 5.3.4 : Cause of major failures

	Metal enclosed				Non metal enclosed					
	Placed in service 1.1.78 - 1.1.83		Placed in service after 1.1.83		Placed in service 1.1.78 - 1.1.83		Placed in service after 1.1.83			
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers		
Design	23.3	7	25.8	16	15.1	13	28.7	82	25.5	95
Manufacture	20.0	6	37.1	23	29.1	25	27.6	79	28.0	104
Inadequate instruction (erect. oper. maint.)	0.0	0	0.0	0	1.2	1	1.4	4	1.3	5
Incorrect erection	13.3	4	1.6	1	2.3	2	10.8	31	8.9	33
Incorrect operation	6.7	2	4.8	3	8.1	7	5.6	16	6.2	23
Incorrect maintenance	13.3	4	1.6	1	5.8	5	1.0	3	2.2	8
Stresses beyond those specified	3.3	1	6.5	4	3.5	3	2.8	8	3.0	11
Other internal causes	10.0	3	4.8	3	2.3	2	5.9	17	5.1	19
Other	10.0	3	17.7	11	32.6	28	16.1	46	19.9	74
Total number of received answers		30		62		86		286		372
		1)		2)		4)		5)		6)

MF = major failure

- 1) Equal to 100% of MF of all the countries
- 2) Equal to 92.5% of MF of all the countries
- 3) Equal to 94.8% of MF of all the countries
- 4) Equal to 96.6% of MF of all the countries
- 5) Equal to 98.9% of MF of all the countries
- 6) Equal to 98.4% of MF of all the countries

Table 53.5 : Cause of minor failures

	Metal enclosed						Non metal enclosed					
	Placed in service 1.1.78 - 1.1.83		Placed in service after 1.1.83		All period		Placed in service 1.1.78 - 1.1.83		Placed in service after 1.1.83		All period	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers
	(%)	answers	(%)	answers	(%)	answers	(%)	answers	(%)	answers	(%)	answers
Design	32.7	83	15.1	59	22.0	142	33.8	290	21.4	383	25.4	673
Manufacture	28.3	72	46.2	180	39.1	252	31.6	271	42.7	765	39.1	1036
Inadequate instruction (erect. oper. maint..)	0.8	2	3.1	12	2.2	14	1.3	11	1.8	32	1.6	43
Incorrect erection	0.8	2	6.9	27	4.5	29	3.0	26	10.0	180	7.8	206
Incorrect operation	3.1	8	1.5	6	2.2	14	4.1	35	5.5	98	5.0	133
Incorrect maintenance	6.3	16	1.0	4	3.1	20	2.2	19	2.6	47	2.5	66
Stresses beyond those specified	1.2	3	1.0	4	1.1	7	2.6	22	1.7	30	2.0	52
Other internal causes	5.9	15	4.6	18	5.1	33	10.3	88	5.3	95	6.9	183
Other	20.9	53	20.5	80	20.7	133	11.1	95	9.1	163	9.7	258
Total number of received answers		254		390		644		857		1793		2650
		1)		2)		3)		4)		5)		6)

mf = minor failure

1) Equal to 98.1% of mf of all the countries

2) Equal to 96.8% of mf of all the countries

3) Equal to 97.3% of mf of all the countries

4) Equal to 98.2% of mf of all the countries

5) Equal to 98.4% of mf of all the countries

6) Equal to 98.3% of mf of all the countries

Table 5.3.6 : Characteristics of the major failures

	All voltages			
	Metal enclosed		Non metal enclosed	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers
Does not close on command	19.7	19	25.8	97
Does not open on command	7.3	7	8.5	32
Closes without command	1.0	1	1.1	4
Opens without command	2.1	2	8.3	31
Does not make the current	2.1	2	1.6	6
Does not break the current	1.0	1	3.5	13
Fails to carry the current	2.1	2	1.3	5
Breakdown to earth	10.4	10	1.3	5
Breakdown between poles	5.2	5	0.5	2
Breakdown across open pole (internal)	1.0	1	4.3	16
Breakdown across open pole (external)	3.1	3	1.1	4
Locking in open or closed position	28.1	27	28.5	107
Others	16.6	16	14.1	53
Total number of received answers		96		375
		1)		2)

1) Equal to 98.9% of MF of all the countries

MF = major failure

2) Equal to 99.2% of MF of all the countries

Table 5.3.7 : Characteristics of the minor failures

	All voltages			
	Metal enclosed		Non metal enclosed	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers
Air or hydraulic oil leakage in operating mechanism	36.5	225	28.9	774
Small SF6 leakage due to corrosion	5.8	36	18.3	492
Small SF6 leakage due to other causes	23.0	142	23.4	627
Change in functional characteristics	8.0	49	16.9	454
Others	26.6	164	12.2	329
Total number of received answers		616		2676
		1)		2)

1) Equal to 93.1% of mf of all the countries

mf = minor failure

2) Equal to 99.3% of mf of all the countries

Table 5.3.8 : Identification of the sub-assembly or component responsible for the major failure

	All voltages			
	Metal enclosed		Non metal enclosed	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers
1. Component at service voltage:				
-Making and breaking units	17.0	16	13.2	50
-Auxiliary interrupters and resistor	2.1	2	1.1	4
-Main insulation to earth	8.5	8	5.0	19
2. Electrical control and auxiliary circuits:				
-Tripping and closing circuits	9.6	9	10.1	38
-Auxiliary switches and associated drives	7.4	7	7.4	28
-Contactors, relays, heaters, thermostats, fuses and other switches, etc.	1.1	1	9.3	35
-Gas density supervision	7.4	7	3.2	12
3. Operating mechanism:				
-Compressor, motors, pumps, pipework fitting	18.1	17	12.4	47
-Energy storage (accumulator, spring)	6.4	6	7.9	30
-Control elements (non electrical)	12.8	12	8.5	32
-Actuators and damping device	2.1	2	10.6	40
-Mechanical transmission	4.3	4	3.7	14
4. Others	3.2	3	7.7	29
Total number of received answers		94 1)		378 2)

1) Equal to 96.9% of MF of all the countries

MF = major failure

2) Equal to 100% of MF of all the countries

Table 5.3.9 : Identification of the sub-assembly or component responsible for the minor failure

	All voltages			
	Metal enclosed		Non metal enclosed	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers
1. Component at service voltage:				
-Making and breaking units	11.8	76	8.8	234
-Auxiliary interrupters and resistor	0.5	3	0.6	17
-Main insulation to earth	7.3	47	24.2	642
2. Electrical control and auxiliary circuits:				
-Tripping and closing circuits	1.4	9	1.5	40
-Auxiliary switches and associated drives	5.6	36	1.2	33
-Contactors, relays, heaters, thermostats, fuses and other switches, etc.	5.1	33	5.5	145
-Gas density supervision	5.0	32	12.1	322
3. Operating mechanism:				
-Compressor, motors, pumps, pipework fitting	19.3	124	18.5	491
-Energy storage (accumulator, spring)	19.9	128	4.1	110
-Control elements (non electrical)	8.4	54	12.4	329
-Actuators and damping device	4.4	28	5.3	140
-Mechanical transmission	2.5	16	1.1	29
4. Others	8.9	57	4.6	121
Total number of received answers		643 1)		2653 2)

1) Equal to 97.1% of mf of all the countries

mf = minor failure

2) Equal to 98.4% of mf of all the countries

6. MAINTENANCE

6.1 Introduction

This chapter forms part of a CIGRE Technical Brochure. In conjunction with the introduction to this brochure it can be read as a separate document.

The total number of circuit-breaker-years, the circuit-breaker population, on which the following study is based, comprises 70708 single pressure SF₆ circuit-breaker-years in the voltage range of 63 kV up to 700 kV and above. The data was received from 132 utilities of 22 countries which answered the CIGRE questionnaire of the Second International Enquiry on single pressure SF₆ circuit-breaker failures and defects in service during the years 1988-1991. The circuit-breakers were described by their rated voltage, the year of installation, the type of location, the type of enclosure and the type of operating mechanism. Each failure was identified by the circuit-breaker component and the stress responsible for it and classified according to a list of suggested failure modes, origins and causes. In addition, information on the consequences of the major failures in terms of circuit-breaker downtime, the time required to obtain spare parts and the existence of a fire and/or explosion of the circuit-breaker was also provided.

A number of questions were asked on each of the two failure cards which are relevant to the subject of maintenance. The questions fall into two broad categories:

6.1.1 Questions relating to the total circuit-breaker population of the survey

- Average interval between scheduled overhaul
- Estimated average labour effort for scheduled overhaul
- Estimated average cost of spare parts consumed for scheduled overhaul

The responses to these questions give a view of maintenance policy across the utilities surveyed but cannot be correlated with the data on failure rates and types of failure.

6.1.2 Questions relating to specific failures

- Date of last overhaul (compared with date of failure or defect)
- Total number of operating cycles since last over-

haul

- Condition of circuit-breaker when the failure or defect was discovered (In service/During maintenance/Others).
- Cause of the failure or defect (Incorrect maintenance/Other causes)

The responses to these questions give a view of how maintenance influences failure rates and types of failures.

The data concerning *Date of last overhaul* was not analysed due to a low level of reporting.

6.1.3 Comparison to the First Enquiry

While similar questions were asked in the First Enquiry, it should be noted that the definitions of overhaul and servicing differed. The First Enquiry defined three types of servicing, *Ordinary servicing*, *Detailed servicing* and *Special servicing*. The Second Enquiry has only a single definition *Overhaul*. Some comparisons between results must therefore be treated with caution.

6.1.4 Age of the circuit-breakers

It is interesting to note that, due to the criteria chosen for the enquiry and the age of the technology, more than 70% of the circuit-breakers in the total survey population were less than 8 years old and the oldest were 14 years old. It is therefore likely that some of the intervals between scheduled overhaul quoted will be based on projections from limited experience with single pressure circuit-breakers.

6.2 Maintenance policies

The responses to the questions in this group were tabulated by voltage class, type of operating mechanism, location indoor/outdoor and metal enclosed/non metal enclosed.

6.2.1 Maintenance frequency

The responses are summarised in Tables 6.2.1/6.2.2. Overall, the average reported interval between scheduled overhaul was 8.3 years with a 50% percen-

Table 6.2.1 : Average interval between scheduled overhaul (years)

Voltage (kV)	Second Enquiry					First Enquiry				
	Number of answers	Average	10% Percentile	50% Percentile	90% Percentile	Number of answers	Average	10% Percentile	50% Percentile	90% Percentile
All Voltages	1901	8.3	5.0	7.9	12.0	463	2.1	1.0	3.0	5.7
63 ≤ V < 100	284	7.6	4.0	6.0	12.0	77	2.3	1.0	3.0	5.0
100 ≤ V < 200	790	8.8	5.0	8.5	15.0	165	2.0	1.0	2.5	5.0
200 ≤ V < 300	332	8.2	4.0	7.9	12.0	127	2.0	1.0	3.0	6.0
300 ≤ V < 500	261	8.2	4.0	7.0	12.0	83	1.4	1.0	2.0	6.0
500 ≤ V < 700	62	8.9	6.0	6.0	12.0	-	-	-	-	-
700 ≤ V	12	13.5	10.0	12.0	20.0	-	-	-	-	-

Note: Results from First Enquiry are for 'Average interval ... between scheduled ordinary servicing', a further definition was given for 'Detailed servicing'. The Second Enquiry has only a single definition, 'Overhaul'.

Table 6.2.2 : Average interval between scheduled overhaul by location and enclosure type (years)

	Number of answers	Average	10% Percentile	50% Percentile	90% Percentile
Indoor and metal enclosed	390	9.3	5.0	10.0	15.0
Indoor and non metal enclosed	87	7.9	5.0	6.0	12.0
Outdoor and metal enclosed	338	8.0	5.0	6.0	12.0
Outdoor and non metal enclosed	1086	8.2	4.0	8.0	12.0

Note: Results from First Enquiry are for 'Average interval ... between scheduled ordinary servicing', a further definition was given for 'Detailed servicing'. The Second Enquiry has only a single definition, 'Overhaul'.

tile of 7.9 years and a 90% percentile of 12 years, the maximum reported was 20 years. This maximum figure is the interval recommended by some manufacturers and is a projection of likely future service experience.

Analysing the results by location and type of enclosure showed little difference from the overall average though the interval for indoor metal enclosed was slightly longer than average (9.3 years). There was no significant difference between the figures reported for different voltage classes.

These results are compared with the equivalent fig-

ures from first survey where the overall average interval was 2.1 years (the definitions of overhaul and servicing did, however, differ between the two enquiries, see note at foot of Tables 6.2.1 and 6.2.2). It is clear that users have made good use of the opportunities offered by changing technology to reduce maintenance frequencies.

It is believed that maintenance intervals are strongly influenced by utility practices. It is the opinion of the experts of the Working Group that maintenance intervals could, in many cases, be extended without an adverse effect on reliability.

**Table 6.2.3 : Estimated average labour effort for scheduled overhaul
(man-hours/year/circuit-breaker)**

Voltage (kV)	Second Enquiry					First Enquiry				
	Number of answers	Average	10% Percentile	50% Percentile	90% Percentile	Number of answers	Average	10% Percentile	50% Percentile	90% Percentile
All Voltages	1585	23.9	4.0	16.0	49.7	446	38.6	10.0	1)	109.0
63 ≤ V < 100	268	15.3	5.0	15.0	32.0	77	19.6	5.0	17.5	30.0
100 ≤ V < 200	601	17.4	3.0	12.0	43.0	164	34.0	10.1	30.0	72.0
200 ≤ V < 300	279	24.8	5.0	15.0	49.7	122	47.4	15.0	44.0	120.0
300 ≤ V < 500	238	31.0	4.8	18.0	56.0	76	48.5	13.6	50.0	169.0
500 ≤ V < 700	50	82.0	16.0	57.0	120.0	-	-	-	-	-
700 ≤ V	9	30.4	24.0	32.0	40.0	-	-	-	-	-

1) The figure published in the final report of the First Enquiry (82.0) is believed to be incorrect.
The original data is now no longer available for checking.

**Table 6.2.4 : Estimated average labour effort for scheduled overhaul by location
and enclosure type
(man-hours/year/circuit-breaker)**

	Number of answers	Average	10% Percentile	50% Percentile	90% Percentile
Indoor and metal enclosed	325	16.0	2.0	12.0	30.0
Indoor and non metal enclosed	76	17.2	3.1	12.0	40.0
Outdoor and metal enclosed	301	28.9	6.0	18.0	57.0
Outdoor and non metal enclosed	883	25.7	4.3	15.0	49.7

6.2.2 Labour effort

The responses are summarised in Tables 6.2.3 and 6.2.4. The estimated average labour effort for scheduled overhaul was reported as 23.9 man-hours/year/circuit-breaker with a 50% percentile of 16 hours and a 90% percentile of 49.7 hours.

Analysing by location and type of enclosure showed indoor equipment requiring approximately 60% of the effort of outdoor but little difference between metal enclosed and non metal enclosed.

As would be expected the average labour effort generally increased with increasing voltage varying from 15.3 hours for equipment < 100 kV to 82 hours for

equipment in the range 500-700 kV.

When drawing conclusions from these results it is important that the make-up of the sub-populations is considered. The proportion of circuit-breakers located indoors is greater in the lower than the higher voltage classes. The apparent lower labour effort in these cases may therefore, in part, only be reflecting the different mix of voltage class in these sub-populations.

The overall average labour effort reported in the First Enquiry for ordinary and detailed servicing combined (effectively equivalent to the definition of scheduled overhaul of the Second Enquiry) was 38.6 man-hours/year/circuit-breaker with a 90% percentile of 109 hours, i.e. approaching twice the figures reported in the Second Enquiry.

**Table 6.2.5 : Estimated cost of spare parts consumed for scheduled overhaul
(man-hours/year/circuit-breaker)**

Voltage (kV)	Second Enquiry					First Enquiry				
	Number of answers	Average	10% Percentile	50% Percentile	90% Percentile	Number of answers	Average	10% Percentile	50% Percentile	90% Percentile
All Voltages	1234	38.1	2.0	10.0	76.2	380	67.6	2.0	15.0	90.0
63 ≤ V < 100	227	25.4	2.0	24.0	61.0	69	55.0	1.0	5.0	60.0
100 ≤ V < 200	467	20.7	2.0	8.0	47.8	138	38.2	1.0	12.0	60.0
200 ≤ V < 300	209	31.6	1.2	12.0	73.5	104	87.5	3.0	20.0	90.0
300 ≤ V < 500	179	17.7	1.7	8.0	47.8	64	72.7	10.0	38.0	157.5
500 ≤ V < 700	32	294.8	40.0	320.0	500.0	-	-	-	-	-
700 ≤ V	0	-	-	-	-	-	-	-	-	-

**Table 6.2.6 : Estimated cost of spare parts consumed for scheduled overhaul by location
and enclosure type
(man-hours/year/circuit-breaker)**

	Number of answers	Average	10% Percentile	50% Percentile	90% Percentile
Indoor and metal enclosed	289	30.9	2.0	7.0	87.0
Indoor and non metal enclosed	67	24.1	2.0	11.0	47.8
Outdoor and metal enclosed	258	86.5	2.0	45.0	303.0
Outdoor and non metal enclosed	620	26.9	1.5	8.0	47.8

6.2.3 Cost of spare parts

In order to obtain a valid comparison between the cost of spare parts in different countries, respondents were asked to express their costs in relation to the local cost per man-hour of labour, this is used as a means of defining a common international currency. The responses are summarised in Tables 6.2.5 and 6.2.6. The estimated average cost of spare parts consumed for scheduled overhaul was reported as man-hours/year/circuit-breaker. The overall average was 38.1 man-hours per year per circuit-breaker with a 50% percentile of 10 and a 90% percentile of 76.2.

Analysing the responses by location and type of enclosure shows non metal enclosed equipment having average costs below the overall average whether located indoors or outdoors. Outdoor metal

enclosed equipment is reported as having average costs significantly higher than the overall average. The average costs analyzed by voltage class show no clear pattern for voltage classes up to 500 kV. In the 500-700 kV voltage class the average cost is reported as 294.8 man-hours per year per circuit-breaker, over seven times the overall average. The number of responses is, however, small with a wide variation in reported costs and it would be unwise to draw any conclusions from this data.

In comparison, the First Enquiry reported an overall average of 67.6 man-hours per year per circuit-breaker with a median of 15 and a 90% percentile of 90.0. From this we can conclude that many users are finding that the cost of spare parts is significantly lower for single pressure SF6 circuit-breakers than for other older technologies.

6.3 Impact of maintenance on failures

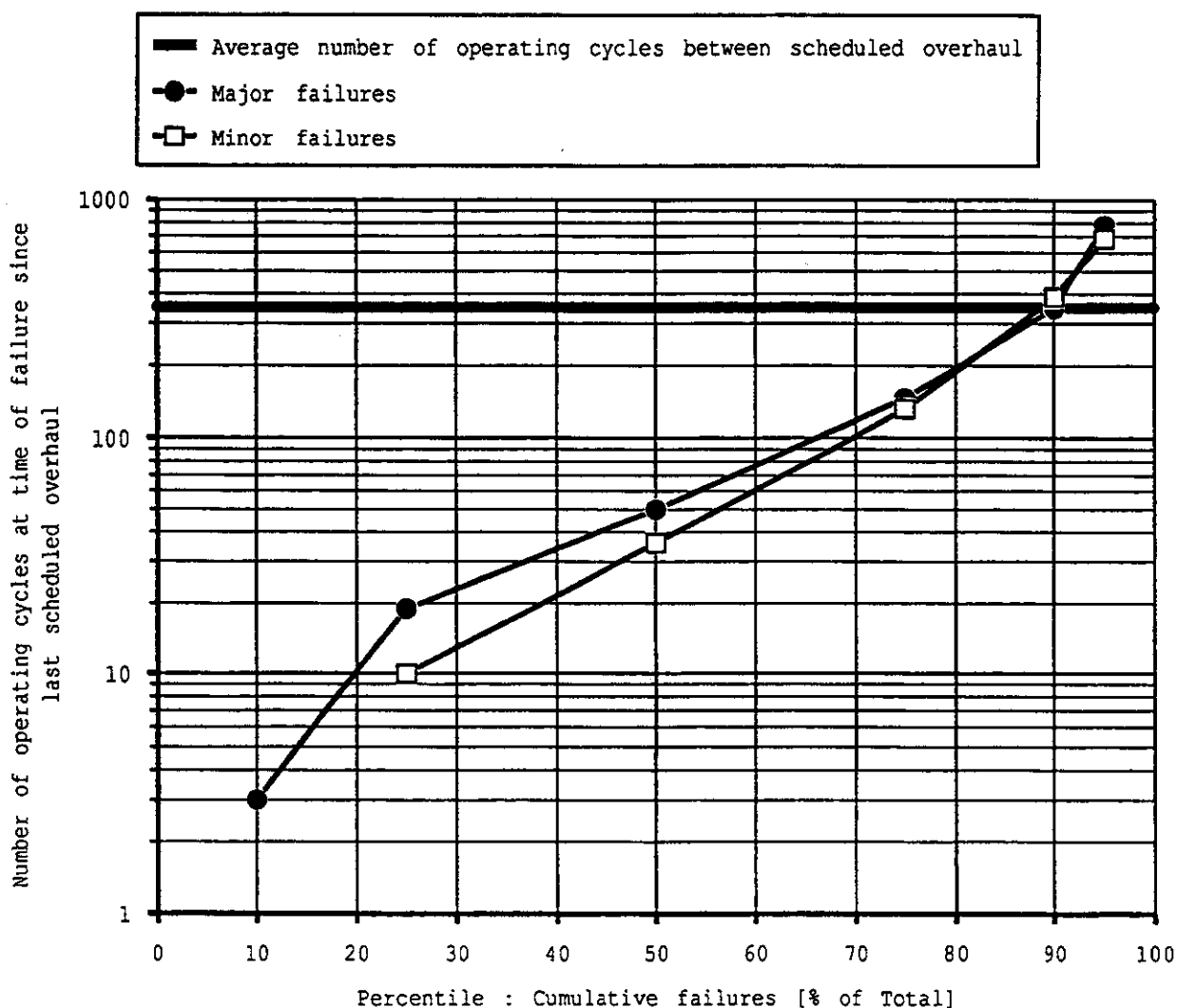
6.3.1 Number of operating cycles from last overhaul to time of the failure

This information was provided on only approximately one third of the failure cards received. Figure 6.3.1 shows the occurrence of major and minor failures plotted against the number of operating cycles at the time of failure since the last overhaul. The average number of operating cycles between scheduled main-

tenance is also shown, this is derived from the average number of operating cycles per year (42) x the average interval between scheduled maintenance (8.3 years) for the total survey population.

This shows that, compared with the average reported number of operating cycles between scheduled maintenance, a large number of failures occur after relatively few operations. It also shows that scheduled maintenance frequencies would have to be reduced significantly to have any serious impact on the number of failures occurring, assuming of course that failures could be prevented by timely maintenance.

Fig. 6.3.1 : Occurrence of failures versus number of operating cycles at the time of failure since the last overhaul



6.3.2 Defects found during maintenance

The responses to the question *Condition of circuit-breaker when the failure or defect was discovered* are shown in Table 6.3.1 with the equivalent results from the First Enquiry. As in the First Enquiry, the number of major failures found during maintenance were very small (6.1% in the Second Enquiry, 4.7% in the First Enquiry). However, it cannot be judged from the results of this enquiry whether maintenance is effective in locating defects prior to a major failure occurring. In particular, 461 minor defects were found during maintenance, almost matching the total number of major failures reported, some of these may subsequently have resulted in major failures if the overhaul had not taken place.

The equivalent figures for minor failures were 25.1%

in the First Enquiry and 13.7% in the Second. Scheduled maintenance is therefore less successful in detecting defects which result in minor failures for single pressure SF6 circuit-breakers than for older technologies.

6.3.3 Defects caused by maintenance

The number of responses to the question *Cause of the failure or defect giving the cause as being Incorrect maintenance* are shown in Table 6.3.2 together with the results from the First Enquiry.

The results for major failures are encouraging, with the proportion of major failures attributed to incorrect maintenance reduced from 8.1% in the First Enquiry to 2.8% in the Second. The equivalent results

Table 6.3.1 : Condition of the circuit-breaker when the failure or defect was discovered

	Second Enquiry				First Enquiry			
	Major failures		Minor failures		Major failures		Minor failures	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers	Percentage (%)	Number of answers
In service or available for service	91.6	434	85.1	2856	91.2	685	69.1	1108
During maintenance	6.1	29	13.7	461	4.7	35	25.1	403
Other cases	2.3	11	1.2	39	4.1	31	5.8	93
Total number of received answers		474		3356		751		1604

Table 6.3.2 : Responses to Question *Cause of failure or defect giving incorrect maintenance as the cause*

	Major failures			Minor failures		
	Percentage (%)	Number of answers	Failures per 100 cb-years	Percentage (%)	Number of answers	Failures per 100 cb-years
Second Enquiry: Placed in service 1.1.78 - 1.1.83	7.8	9	-	3.2	35	-
Second Enquiry: Placed in service after 1.1.83	1.1	4	-	2.3	51	-
Second Enquiry: All period	2.8	13	0.018	2.6	86	0.122
First Enquiry: All period	8.1	61	0.078	4.5	72	0.092

cb = circuit-breaker

Table 6.3.3 : Component responsible for the failure where the cause was given as incorrect maintenance

	Major failures		Minor failures	
	Percentage (%)	Number of answers	Percentage (%)	Number of answers
1. Component at service voltage:				
-Making and breaking units	7.7	1	4.7	4
-Auxiliary interrupters and resistor	0.0	0	0.0	0
-Main insulation to earth	15.4	2	12.8	11
2. Electrical control and auxiliary circuits:				
-Tripping and closing circuits	30.8	4	2.3	2
-Auxiliary switches and associated drives	15.4	2	1.2	1
-Contactors, relays, heaters, thermostats, fuses and other switches, etc.	0.0	0	1.2	1
-Gas density supervision	7.7	1	4.7	4
3. Operating mechanism:				
-Compressor, motors, pumps, pipework fitting	15.4	2	27.9	24
-Energy storage (accumulator, spring)	0.0	0	5.8	5
-Control elements (non electrical)	7.7	1	31.4	27
-Actuators and damping device	0.0	0	0.0	0
-Mechanical transmission	0.0	0	4.7	4
4. Others	0.0	0	3.5	3

failure where the cause was given as *Incorrect maintenance*.

Table 6.3.4 : Characteristic of the major failure where the cause was given as incorrect maintenance

Characteristic	Percentage (%)	Number of answers
Does not close on command	23	3
Does not open on command	8	1
Opens without command	23	3
Breakdown to earth	23	3
Locked in open or closed position	23	3

for minor failures are 4.5% in the First Enquiry and 2.6% in the Second. There is, however, still room for improvement in this area.

Table 6.3.3 shows the component responsible for the

For major failures, the only component which stands out as being exceptionally prone to defects caused by incorrect maintenance is the tripping and closing circuits. However, even in this case, the number of incidents is extremely low.

For minor failures, the operating mechanism appears to be the main area of vulnerability with 60% of the *Incorrect maintenance* failures reported as being in this part of the circuit-breaker. This would be expected since maintenance is often focussed on the operating mechanism.

Table 6.3.4 shows the characteristic of the major failure where the cause was given as incorrect maintenance. This shows that the most likely consequence of incorrect maintenance is a failure of the circuit-breaker to operate, either due to locking or failing to respond to a command.

Breakdown to earth is also a significant characteristic. It must, however, be stressed that the number of occurrences is extremely low.

6.4 Conclusions

Great care must be taken in interpreting the data in this Chapter. The enquiry did not allow any correlation between *Maintenance policy* and failure rates, it is therefore impossible to judge the effectiveness of the reported maintenance regimes. The way in which the data has been collected and analysed is also, in some cases, not statistically rigorous. However, it is probably reasonable to consider the general trends arising from the data.

The main conclusions that can be drawn are as follows:

Relating to the total circuit-breaker population

- * Average maintenance intervals are approximately four times those reported in the First Enquiry. However, due to the different definitions of *Ordinary servicing* and *Scheduled overhaul* the results are not directly comparable.
- * The average labour effort for scheduled overhaul has been reduced by almost 40% compared with the First Enquiry.
- * The average cost of spare parts is now approximately 50% of the figure reported in the First Enquiry.
- * Outdoor metal enclosed circuit-breakers have spare parts costs significantly higher than average.
- * Indoor circuit-breakers require significantly lower

labour effort for scheduled overhaul than average.

- * There is a wide spread of policy and experienced costs between the participating utilities. It has not been possible to determine which maintenance regimes are most effective in preventing failures in service.

Relating to Specific Failures

- * There has been a significant reduction in the number of major failures and minor failures caused by incorrect maintenance compared with the First Enquiry. The figure is now very low.
- * Comparatively few defects are found during maintenance, it can therefore be concluded that an increase in maintenance frequencies would not significantly improve detection of defects prior to failures occurring in service. However, the converse may not be true and reducing maintenance frequencies may have an impact on reliability.
- * There is some evidence that failures in service tend to occur relatively soon after scheduled maintenance (see Figure 6.3.1). Once again, this would suggest that increasing maintenance frequencies would not significantly improve detection of defects prior to failures occurring in service.
- * The results of this enquiry should be treated with caution, the population of the survey is young and many circuit-breakers included may not have received a first scheduled overhaul.

7. DIAGNOSTIC TECHNIQUES

CIGRE WG 13.06 has published two reports on diagnostic techniques. One report, published at the CIGRE Session in Paris in 1992, deals with the more general aspects of the development and application of diagnostic techniques [8]. The other report points at the items and parameters that should be observed from a point of view of improvement of the reliability of the circuit-breaker. The second report has been published at the CIGRE Symposium on diagnostic and maintenance techniques in Berlin in 1993 [9].

Both reports are attached as appendix F and G, respectively.

8. IMPACT ON TESTING TO IMPROVE RELIABILITY

8.1 Introduction

This chapter forms part of a CIGRE Technical Brochure. In conjunction with the introduction to this brochure it can be read as a separate document.

The total number of circuit-breaker-years, the circuit-breaker population, on which the following study is based, comprises 70708 single pressure SF6 circuit-breaker-years in the voltage range of 63 kV up to 700 kV and above. The data was received from 132 utilities of 22 countries which answered the CIGRE questionnaire of the Second International Enquiry on single pressure SF6 circuit-breaker failures and defects in service during the years 1988-1991. The circuit-breakers were described by their rated voltage, the year of installation, the type of location, the type of enclosure and the type of operating mechanism. Each failure was identified by the circuit-breaker component and the stress responsible for it and classified according to a list of suggested failure modes, origins and causes. In addition, information on the consequences of the major failures in terms of circuit-breaker downtime, the time required to obtain spare parts and the existence of a fire and/or explosion of the circuit-breaker was also provided.

The reliability of a circuit-breaker is very important to guarantee for the safety of the energy supply. Thus one of the most reasonable questions seems to be : Could some of the reported failures in the enquiry

have been prevented by an adequate test or test procedure in advance during development or manufacturing of the circuit-breaker or even after erection on-site, in order to avoid them during service ?

The aim of this study is to reveal the evidence of testing regarding the reliability and availability of circuit-breakers, particularly of single pressure SF6 circuit-breakers. Therefore the objectives are:

- to summarize general information about test procedures and test duties
- to give general information about major and minor failures distribution,
- to check which correlations do exist between today's testing processes and the occurrence of failures and failure modes in service
- to conclude about the adequacy of the existing test procedures / test duties and to conclude about the possible necessity of new tests.

Reliability, as a result of a high quality level, can not be tested into an equipment or an apparatus; it must be integrated part of the design / development process and of the manufacturing process as well. Thus the need of extended tests in order to improve reliability has to be considered carefully and only adequate and realistic test procedures should be proposed to reach the goals of reliable circuit-breakers.

Fig. 8.1.1 : Revealing of critical sub-assemblies

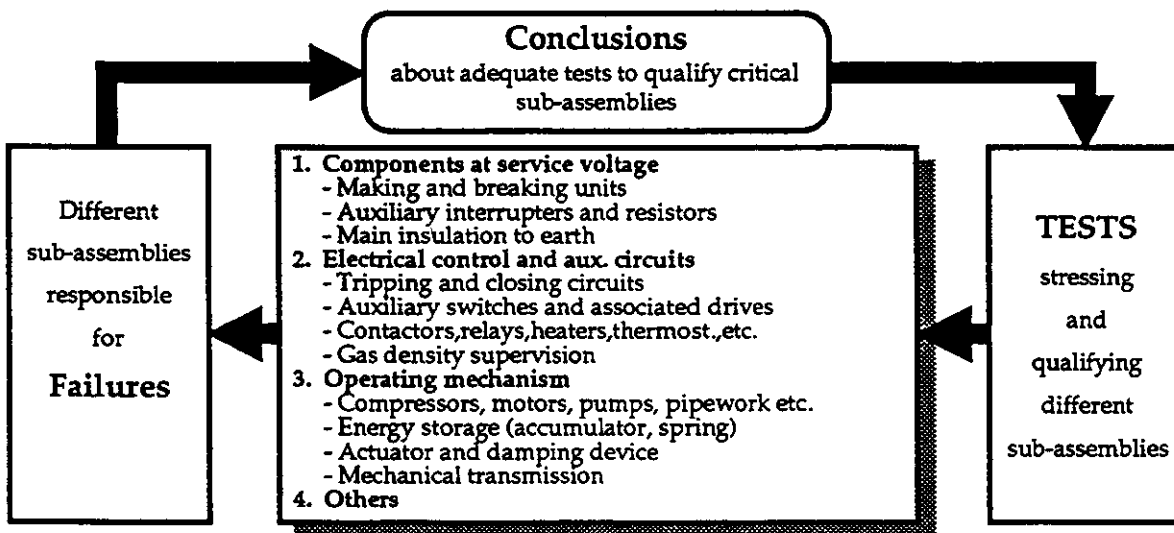
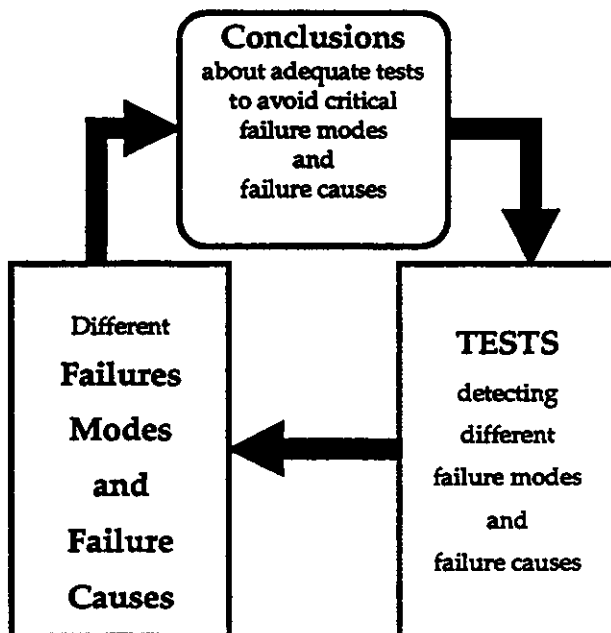


Fig. 8.1.2: Revealing of critical failure modes and failure causes



This study follows a two way approach to investigate the impact on testing on the base of the Second CI-GRE Enquiry:

1. Revealing of critical sub-assemblies
2. Revealing of critical failure modes and failure causes

The first approach asks the question about the existence of components of the breaker, causing high numbers of failures, which probably could be substantially improved by strict application of tests, in order to reduce failures in service. Figure 8.1.1 illustrates this approach. The second approach asks the question about the existence of special failure modes or failure causes, occurring more often than others or being more critical than others, which probably could be reduced by strict application of tests during development or manufacturing. Figure 8.1.2 illustrates this second approach.

8.2 Objectives and Classification of Testing: State of the art and prospect

Regarding the lifetime of a circuit-breaker type a sequence of different test procedures will be found. For instance an evident difference exists between a de-

sign / development test and an on site test. Thus the following classification defines the different test procedures applied to get a circuit-breaker from the very first idea, through the put in service at the customers site and finally to the end of its life.

1. Design and development testing.

These tests are done in a very early stage of a development. They are not under consideration for this investigation of impact on testing because the material under test is very often not finally defined.

2. Type testing.

These tests, being the final verification of the design, will be of great importance for the in-service-behaviour of the breaker or the apparatus in general. The procedure of type testing is well defined in a great variety of international standards (IEC, ANSI etc.). Anyway, we will have to consider these tests very carefully concerning additional or better defined procedures of testing in order to improve breakers reliability and availability

3. Routine testing.

These tests, being the final check of the manufacturing process, have to prove, by doing a defined set of tests in accordance to some type tests (mainly functional tests), the good operation of each specimen of a series of manufactured circuit-breakers.

4. On-site testing

These tests, being the final check before put into service, have to prove by repeating reasonable parts of the routine testing, the integrity of the equipment after transportation and erection. It means that on-site testing has to reveal defects caused by transport and/or erection.

5. Inspections and diagnostic testing during service

After the on-site test the operation and maintenance starts, with its own inspections, diagnostic tests and monitoring techniques. These tests are not under consideration for this investigation but for a separate one dealing with diagnostics. (See chapter 7 of this Technical Brochure.)

6. Requalification testing

Repeated type tests are done to verify that the original type tests, done with the first objects from the production line are still valid after a certain production period. Other purposes are the verification of small alterations in the product or the production process and the verification that the type tests are valid for the whole population by randomly taking test objects.

Regarding the functions of a circuit-breaker a different classification of tests and test procedures has to be applied. In that case the distinction between

mechanical,
climate,
temperature rise,
dielectric and
power testing (making and breaking tests)

has to be made where each kind of tests consists of one or several test duties. Table 8.2.1 gives a list of the most important examples of test duties. The table must not to be considered as definitely complete. This systematic is actually clearly defined in the existing IEC-standards as well as in the ANSI-standards. Certainly there are numerous national standards in accordance with IEC/ANSI following the same systematic. The today's IEC procedure for HV-circuit-breaker testing is basically fixed in IEC 56 and IEC 694, whilst the ANSI procedure is mainly compiled within the ANSI C37 series. These two standard

packages cover rather completely the circuit-breaker population of the CIGRE enquiry. Thus, thinking about impact on testing, these publications have to be kept in mind.

Standards are definitely not static and therefore under continuous change by adding amendments or complete revisions. Regarding the IEC circuit-breaker package some outstanding changes in test procedures, proposed or already introduced, are:

- Dielectric condition check after type tests (Amendment 1 to IEC 56)
- Extended mechanical endurance (Still under consideration by IEC TC17)
- Electrical endurance (Still under consideration by IEC TC17)
- Identification of switchgear under type test (Still under consideration by IEC TC17)

This list could certainly be extended. Anyway the

Table 8.2.1 : Examples of test duties

<i>Kind of test:</i>	<i>Test duties:</i>
General	•Quality check
Mechanical Tests	•Mechanical Performance •Mechanical Endurance •Timing Test •Functional Test •Tightness Test
Climate Tests (environmental tests)	•Low Temperature Test •High Temperature Test
Temperature Rise Tests	•Temperature Rise Test •Main Contact Resistance Test
Dielectric Tests	•AC Tests combined with PD-Detection •Lightning Impulse Tests •Switching Impulse Tests •AC Tests on auxiliary equipment •Impulse Tests on auxiliary equipment
Power Tests (making and breaking)	•Test Duties 1 to 5 applied to: -Critical current tests -Short-line fault tests -Single-phase short-circuit tests -Out-of-phase making and breaking tests -Capacitive current switching tests -Small inductive current switching tests •Short time current test

prospective changes in the existing standards have to be considered later on, when making conclusions.

8.3 Impact of different test duties on sub-assemblies or failure modes

When performing tests different sub-assemblies will be stressed seriously and thus qualified by different kind of tests or test duties. For instance, the operating mechanism will normally not be affected by the die-

lectric or the temperature rise test. Table 8.3.1 gives correlation between the sub-assemblies and the kind of tests stressing them. The table tries to give an answer to the question if a certain test duty stresses, and therefore qualifies, a sub-assembly.

Following the second approach mentioned in the introduction above, Table 8.3.2 gives correlation between the failure modes and the kind of tests. This table attempts to give answer to the question if a cer-

Table 8.3.1 : Correlation between sub-assemblies and tests stressing / qualifying them

	Mechanical Test	Climate Test	Temperature Rise Test	Dielectric Test	Power Test
Relevant test procedures: (Tests in brackets: Not mandatory)	Type tests Routine tests On-site tests (In-Service checks)	(Type tests)	Type tests (In-Service checks)	Type tests Routine tests On-site tests (In-Service checks)	Type tests
1. Components at service voltage					
-Making and breaking units	++	++	++	++	++
-Auxiliary interrupters and resistors	++	++	+	++	++
-Main insulation to earth	+	+	0	++	+
2. Electr. control and aux. circuits					
-Tripping and closing circuits	++	++	0	0	+
-Auxiliary switches and ass. drives	++	++	0	+ 1),2)	0
-Contactors relays heaters ...	+	++	0	0	0
-Gas density supervision	++	++	+	+ 1),2)	0
3. Operating mechanism					
-Compressor motors pumps	++	++	0	0	0
-Energy storage (accumul. , springs)	++	++	0	0	+
-Control elements (non electrical)	++	++	0	0	+
-Actuators and damping device	++	++	0	0	+
-Mechanical transmission	++	++	0	0	+
4 Others	-	-	-	-	-
Explanations:	0	:	No significant stress		
	+	:	Some stress		
	++	:	Strong stress		
	-	:	Undefined		
Note 1 : Auxiliary equipment being under dielectric testing itself has to be considered as stressed strongly.					
Note 2 : Future auxiliary equipment, using electronics, may be stressed strongly during dielectric testing of the breaker by EMC phenomena.					

tain kind of tests or test duty will likely detect failures during type testing, routine testing or even on-site testing. Table 8.3.1 and Table 8.3.2 are based on today's commonly used testing procedures in accordance with current standards and do not represent data from the CIGRE enquiry. The correlation between the different testing procedures (Type testing, routine testing, on-site testing) and some of the failure causes are already stated in Chapter 8.2 by the classification of testing. The list of sub-assemblies in Table 8.3.1

and for failure modes in Table 8.3.2 are exactly the same as used in the Questionnaire Cigré 13-88(WG06) 03. (See appendix B.)

Regarding Table 8.3.1 the mechanical tests definitely turn out to be the most stressing ones for the majority of the sub-assemblies of a circuit-breaker. From that result Table 8.3.2 is rather different. Both, the mechanical and the power testing show as an average a high failure detection potential.

Table 8.3.2 : Correlation between failure modes and tests detecting them

	Mechanical Test	Climate Test	Temperature Rise Test	Dielectric Test	Power Test
Relevant test procedures: (Tests in brackets: Not mandatory)	Type tests Routine tests On-site tests (In-Service checks)	(Type tests)	Type tests (In-Service checks)	Type tests Routine tests On-site tests (In-Service checks)	Type tests
Major failures					
Does not close on command	++	+	0	0	(+)
Does not open on command	++	+	0	0	(+)
Closes without command	++	0	0	0 1)	0 1)
Opens without command	++	0	0	0 1)	0 1)
Does not make the current	0	0	0	0	++
Does not break the current	0	0	0	0	++
Fails to carry current	0	0	++	0	+
Breakdown to earth	0	0	0	++	+
Breakdown between poles	0	0	0	++	+
Breakdown across open pole (internal)	0	0	0	++	++
Breakdown across open pole (external)	0	0	0	++	++
Locking in open or close position	++	+	0	0	+
Others	-	-	-	-	-
Minor failures					
Air or hydr. oil leakage in operating mech.	++	++	0	0	0
Small SF6 leakage due to corrosion	0	(+)	0	0	0
Small SF6 leakage due to other causes	++	++	(+)	0	0
Change in functional characteristics	++	++	+	+	+
Others	-	-	-	-	-
Explanations:	0	:	No significant detection potential		
	(+)	:	Only slight detection potential		
	+	:	Some detection potential		
	++	:	Strong detection potential		
	-	:	Undefined		
<i>Note 1 : Future auxiliary equipment, using electronics, may cause failure modes like Closes/Opens without command by EMC phenomena.</i>					

8.4 Identification of critical sub-assemblies

The first step of identifying the critical sub-assemblies is highlighting the greatest numbers of failures in Table 8.4.1 and Table 8.4.2 which give the correlation between sub-assemblies and the origin of the failures for major failures and minor failures respectively.

The outstanding figures are obvious. For both, the major failures in Table 8.4.1 as well as the minor failures in Table 8.4.2 the operating mechanism is a very critical sub-assembly being responsible for a great number of failures or defects. For the major failures the greatest number is indeed kept by the operating mechanism followed by the electrical control and auxiliary circuits, especially by tripping and closing circuits.

The distribution of the minor failures shows a different shape, where the main insulation to earth is the most critical sub-assembly which is strongly influenced by tightness problems of the SF₆-gas system. Compressor, motors, pumps also represent a critical sub-assembly concerning minor failures.

The second step to learn more about how critical sub-assemblies are, is to correlate them to the failure mo-

des which are also called the characteristics of the failures.

Table 8.4.4 reveals the same thing as seen before in Table 8.4.1 : The highest number of major failures is represented by the 28 cases of locked circuit-breakers in open or closed position where compressor, motors, pumps, etc. of the operating mechanism are responsible for the failure. Evaluating Table 8.4.5 exactly the same sub-assembly responsible for the majority of the minor failures will be found. In 401 cases air or hydraulic oil leakage was detected, where responsibility had to be put to compressors, motors etc.

Coming back now to the question if emphasis on some tests should be given as a result of the enquiry one has to return to Table 8.2.1 and Table 8.3.1 in order to find the adequate tests and test duties. It is quite obvious that the most critical sub-assemblies (*Electrical control and auxiliary circuits, Operating mechanism*) are mainly, even nearly exclusively, stressed, and thus qualified, by mechanical and climate testing. In the case of mechanical testing the endurance test is likely to have the greatest influence whereas in the case of the climate testing the influence of both, the low and high temperature test, is to consider as equal.

Table 8.4.1 : Correlation between sub-assemblies responsible for the failure and the origin of the major failure (Number of failures)

Major failures	Sum of failures	Origin				
		Mechanical in operating mechanism	Mechanical in other parts	Electrical (main circuit)	Electrical (auxiliary and control circuit)	Tightness of SF ₆ -gas system
Total number of answers:	459	202	48	64	113	32
1. Components at service voltage	96					
-Making and breaking units	66	2	15	42	1	6
-Auxiliary interrupters and resistors	5	1	1	2	1	0
-Main insulation to earth	25	2	4	8	0	11
2. Electrical control and aux. circuits	136					
-Tripping and closing circuits	46	7	0	2	37	0
-Auxiliary switches and ass. drives	35	9	2	1	23	0
-Contactors relays heaters ...	36	2	1	0	33	0
-Gas density supervision	19	3	5	0	6	5
3. Operating mechanism	261					
-Compressor motors pumps	61	42	9	0	9	1
-Energy storage (accumul., springs)	36	35	0	0	0	1
-Control elements (non electrical)	44	38	3	0	3	0
-Actuators and damping device	42	40	2	0	0	0
-Mechanical transmission	18	12	3	0	0	3
4. Others	26	9	3	9	0	5

Table 8.4.2 : Correlation between sub-assemblies responsible for the failure and the origin of the minor failure (Number of failures)

Minor failures	Sum of failures	Origin					Tightness of SF6-gas system
		Mechanical in operating mechanism	Mechanical in other parts	Electrical (main circuit)	Electrical (auxiliary and control circuit)		
Total number of answers:	3179	1266	318	29	330	1236	
1. Components at service voltage	1006						
-Making and breaking units	301	7	25	22	3	244	
-Auxiliary interrupters and resistors	19	2	10	2	0	5	
-Main insulation to earth	686	5	20	1	2	658	
2. Electrical control and aux. circuits	618						
-Tripping and closing circuits	47	13	3	2	27	2	
-Auxiliary switches and ass. drives	68	7	8	0	52	1	
-Contactors relays heaters ...	165	6	6	0	150	3	
-Gas density supervision	338	43	58	0	61	176	
3. Operating mechanism	1386						
-Compressor motors pumps	573	442	83	1	13	34	
-Energy storage (accumul., springs)	231	192	35	0	1	3	
-Control elements (non electrical)	375	333	20	0	15	7	
-Actuators and damping device	164	145	13	0	1	5	
-Mechanical transmission	43	28	10	0	0	13	
4. Others	169	51	27	1	5	85	

Table 8.4.3 : Estimated average number of operating cycles per circuit-breaker per year and per lifetime (Lifetime evaluated only for all voltages)

	Voltage classes (kV)							Lifetime	
	63≤V<100	100≤V<200	200≤V<300	300≤V<500	500≤V<700	700≤V	All	25 years	40 years
Average	47	40	39	36	46	25	42	1050	1680
10% Percentile	24	10	19	13	15	8	13	325	520
50% Percentile	48	25	20	20	44	40	30	750	1200
75% Percentile	50	46	25	33	60	40	50	1250	2000
90% Percentile	84	60	55	82	68	45	76	1900	3040
95% Percentile	84	96	100	89	72	45	84	2100	3360
Maximum	450	620	1600	1760	199	45	1760	—	—

Regarding the mechanical endurance test the total amount of performed switching operation does not seem to be the critical item. In fact the estimated 90% percentile number of operating cycles per year for the majority of the circuit-breakers is not more than about 80 cycles, whereas the occurrence of higher numbers of cycles seems to be restricted to some exceptional applications of circuit-breakers. Refer to Table 8.4.3 for the statistical distribution of the estimated average number of operating cycles. In spite of these

figures the question of mechanical endurance tests will be discussed in depth in sub-chapter 8.7.

Regarding a possible improvement of power and dielectric testing, which will mainly, or even nearly exclusively, only qualify the making and breaking units and the main insulation, it is difficult to find good reasons and motivation to introduce any changes. In fact, Table 8.4.1 shows clearly that only 11% (52/475 failures) of the major failures have their origin and

Table 8.4.4 : Correlation between sub-assemblies responsible for the failure and the characteristics (failure mode) of the major failure (Number of failures)

	Sum of failures	Major failure modes											Locking in open or closed position	Others
		Does not close on command	Does not open on command	Closes without command	Opens without command	Does not make the current	Does not break the current	Fails to carry the current	Breakdown to earth	Breakdown between poles	Breakdown across (internal) open pole	Breakdown across (external) open pole		
Total number of answers:	468	116	39	5	13	8	14	7	15	7	17	7	133	67
1. Components at service voltage	97													
-Making and breaking units	66	1	2	0	1	1	11	3	8	7	10	4	8	10
-Auxiliary interrupters and resistors	6	0	0	0	1	0	0	0	0	0	2	0	1	1
-Main insulation to earth	25	0	1	0	4	1	1	1	6	0	0	2	6	3
2. Electrical control and aux. circuits	136													
-Tripping and closing circuits	47	22	13	1	7	0	0	1	0	0	0	0	3	0
-Auxiliary switches and ass. drives	35	16	6	0	1	2	0	0	0	0	0	0	6	5
-Contactors relays heaters ...	36	24	2	0	0	0	0	2	0	0	0	0	8	0
-Gas density supervision	18	1	0	0	0	0	0	0	0	0	0	0	14	0
3. Operating mechanism	203													
-Compressor motors pumps	63	9	1	2	3	3	0	0	0	0	0	1	25	16
-Energy storage (accumul. , springs)	36	7	3	0	3	0	0	0	0	0	1	0	19	3
-Control elements (non electrical)	44	14	6	1	1	0	0	0	0	0	0	0	11	7
-Actuators and damping device	42	11	2	1	5	0	1	0	0	0	0	0	18	4
-Mechanical transmission	18	6	2	0	3	0	0	0	0	0	0	0	7	0
4. Others	32	2	0	0	2	0	1	0	1	0	4	0	4	18

Table 8.4.5 : Correlation between sub-assemblies responsible for the failure and the characteristics (failure mode) of the minor failures (Number of failures)

	Sum of failures	Minor failure modes				Others
		Air or hydr. oil leakage (op. mech.)	Small SF6 leakage due to corrosion	Small SF6 leakage due to other causes	Change in functional characteristics	
Total number of answers:	3270	990	522	729	541	488
1. Components at service voltage	1016					
-Making and breaking units	308	8	24	176	9	31
-Auxiliary interrupters and resistors	20	7	2	4	5	2
-Main insulation to earth	688	3	398	258	7	30
2. Electrical control and aux. circuits	640					
-Tripping and closing circuits	48	11	1	1	20	15
-Auxiliary switches and ass. drives	67	4	0	1	39	23
-Contactors relays heaters ...	174	1	1	2	92	78
-Gas density supervision	351	2	16	141	138	54
3. Operating mechanism	1437					
-Compressor motors pumps	610	401	2	40	67	100
-Energy storage (accumul. , springs)	236	129	0	7	50	50
-Control elements (non electrical)	381	278	0	6	78	19
-Actuators and damping device	166	114	1	9	26	16
-Mechanical transmission	44	8	2	17	5	12
4. Others	177	24	23	67	5	58

the sub-assembly responsible for the failure on the electrical main circuit. That means in other words, power and dielectric testing on circuit-breakers could be extended excessively without having an influence on reliability of more than about 10% in the very best case!

8.5 Identification of critical failure modes and failure causes

Tables 8.4.4 and 8.4.5 can also be used to identify critical failure modes. Furthermore the correlation between failure modes and origin is helpful to reveal critical failure characteristics. This relationship for major failures is given in Table 8.5.1, while Table 8.5.2 gives the pure distribution of the characteristics of the minor failures (minor failure modes).

An investigation of the causes of the failures is very important with respect to a possible impact on testing. The expectation is to find hints concerning the application of the adequate test procedure. The aim of such an investigation is to find out if one of the above defined test procedures, design/development testing, type testing, routine testing or on-site testing

(see Chapter 8.2) has to be modified in order to improve reliability.

Regarding the Major Failures two outstanding modes have to be considered. *Does not close on command* and *Locking in open or closed position* represent the two failure characteristics with the highest numbers of failures and therefore have to be considered as the critical major failure modes. Keeping that result in mind, and referring back to Table 8.3.2 it is obvious that mechanical testing turns out to be, as already seen above, very important.

The situation of the minor failures is rather clear. As already learned from Table 8.4.2, Table 8.4.5 reveals again, after the operating mechanism, the tightness of the SF6-gas system in general to be the second most critical item giving a total of more than 1250 failures which means about nearly 40% of all minor failures. The tightness problem as a common one could even be considered as the one and only problem at all, if one counts also the minor failures of the mode Air or hydraulic oil leakage in operating mechanism, representing about another 1000 failures. This would reveal about 67% of the minor failures to be tightness failures. Another time mechanical and climate testing turn out to be the most important ones, when making

Table 8.5.1 : Correlation between the characteristics (failure mode) of the failure and the origin of the major failure (Number of failures)

Major failures	Sum of Failures	Origin				
		Mechanical in operating mechanism	Mechanical in other parts	Electrical (main circuit)	Electrical (auxiliary and control circuit)	Tightness of SF6-gas system
Total number of answers:	458	203	47	64	113	31
Does not close on command	115	50	9	1	55	0
Does not open on command	39	16	3	0	19	1
Closes without command	5	5	0	0	0	0
Opens without command	32	19	1	3	4	5
Does not make the current	8	3	1	1	2	1
Does not break the current	14	1	2	9	0	2
Fails to carry the current	7	0	0	4	3	0
Breakdown to earth	15	0	1	14	0	0
Breakdown between poles	7	0	3	4	0	0
Breakdown across open poles (internal)	16	5	2	8	1	0
Breakdown across open poles (external)	6	0	0	5	0	1
Locking in open or closed position	132	69	18	1	25	18
Others	62	35	7	14	3	3

Table 8.5.2 : Correlation between the characteristics (failure mode) of the failure and the origin of the minor failure (Number of failures)

Minor failures	Sum of Failures	Origin				
		Mechanical in operating mechanism	Mechanical in other parts	Electrical (main circuit)	Electrical (auxiliary and control circuit)	Tightness of SF6-gas system
Total number of answers:	3209	1268	312	29	322	1278
Air or hydraulic oil leakage in op.mech.	956	837	108	4	2	5
Small SF6 leakage due to corrosion	527	5	1	0	1	520
Small SF6 leakage due to other causes	759	23	35	1	2	698
Change in functional characteristics	531	204	94	6	200	27
Others	436	199	74	18	117	28

correlation between these figures and Table 8.3.2.

A special attention should be paid to the breakdowns, being one of the very severe failures.

Table 8.5.3 indicates 46 cases of breakdowns to earth, between poles and across open poles, which is about 10% of all the major failures. Regarding the impact on testing, the question is, if such a percentage calls for modified or improved dielectric testing. Table 8.5.3 gives correlation between the different breakdown modes and their causes. One third of the failures is caused by *Other*, one third by different causes including *Incorrect erection / operation* and an other

third is caused by *Design / Manufacture*. In principle design and manufacturing can be observed by tests. In the particular case of breakdown failures this observation is mainly done by the application of dielectric type tests and in conjunction with switching operations also by the application of power tests. Putting the enquiry's breakdown failure figures into relation to the investigated circuit-breaker population (70708 cb-years) the result turns out to be very interesting:

- The meantime-between-failure (MTBF) for all breakdown modes is 1537 years.
- The MTBF for the breakdowns caused by design

**Table 8.5.3 : Correlation between breakdown and the causes of the failures
(Number of failures)**

	Breakdown failure causes								
	Design	Manufacture	Inadequate instructions for erection	Incorrect erection	Incorrect operation	Incorrect maintenance	Stresses beyond those specified	Other external causes	Other
Relevant test procedure:	Type tests	Routine tests	On-site tests	On-site tests	--	Checks	--	--	--
Total number of answers:	7	8	0	3	2	3	2	6	15
Breakdown to earth	2	2	0	0	0	3	0	2	6
Breakdown between poles	2	3	0	0	0	0	1	1	0
Breakdown across open poles (internal)	2	2	0	2	2	0	1	0	8
Breakdown across open poles (external)	1	1	0	1	0	0	0	3	1

or manufacture is 4714 years which is a rather long period.

These figures let it appear very unlikely to improve reliability substantially by application of more and more severe dielectric tests during type testing or routine testing of circuit-breakers.

The last question to answer was already raised before: Is there one of the yet well established test procedures (type testing, routine testing, on-site testing) to be improved as a consequence of the enquiry's data? The majority of failures, for both the major and the minor failures, is caused by manufacturing followed by the design. That is the message of Tables 8.5.4 and 8.5.5. Going into details it becomes obvious that the operating mechanism, with some of its components, is another time the crux, especially for the major failures. Regarding minor failures, Table 8.5.5 in conjunction with Table 8.4.2 reveals that tightness of SF₆-gas system, followed by some components of the operating mechanism, are the most critical items concerning failure causes named *Design* or *Manufacture*.

Hence, another time, emphasis has to be given to mechanical and climate testing in order to get substantial improvements. The amount of failures due to *Design* or *Manufacture* is the highest one. That reveals for both, the major failures as well as the minor failures, where the cause *Manufacture* is responsible for a

majority of failures, especially in the case of the minor failures. Therefore type testing and routine testing are the most important test procedures.

8.6 Comparison to the First International Enquiry

The observations from the First Enquiry regarding sub-assemblies, failure modes and failure causes cope more or less with those from the Second Enquiry:

- The most critical sub-assemblies responsible for failures have been and still are the *Electrical control and auxiliary circuits* and the *Operating mechanism*.
- The majority of failures (MF and mf) have been and still are caused by *Design* and *Manufacture*.
- The major failure modes *Does not close on command* and *Does not open on command* have been and still are amongst the critical ones.

The comparison of the failure rates is very interesting: The major failure rate has practically been halved for the second enquiry, whereas the minor failure rate has slightly increased. This increase has to be considered carefully because of a new very critical failure origin for the Second Enquiry which is the tightness of the SF₆-gas system.

Table 8.5.4 : Correlation between sub-assemblies responsible for the failure and the causes of the major failures (Number of failures)

	Major failure causes									
	Design	Manufacture	Inadequate instruction for erection	Incorrect erection	Incorrect operation	Incorrect maintenance	Stresses beyond those specified	Other external causes	Other	
	Type tests	Routine tests	On-site tests	On-site tests	--	Checks	--	--	--	
Relevant test procedure:	137	133	5	38	28	13	15	25	--	88
Total number of answers:										
1. Components at service voltage										
-Making and breaking units	15	15	0	7	4	1	7	6		9
-Auxiliary interrupters and resistors	1	2	0	1	0	0	0	1		1
-Main insulation to earth	6	6	0	1	0	2	1	2		7
2. Electrical control and aux. circuits										
-Tripping and closing circuits	10	12	1	4	2	4	0	2		12
-Auxiliary switches and ass. drives	2	10	0	6	7	2	0	0		8
-Contactors relays heaters ...	7	14	0	1	2	0	1	7		4
-Gas density supervision	1	10	0	4	0	1	0	0		1
3. Operating mechanism										
-Compressor motors pumps	19	22	0	2	1	2	3	3		9
-Energy storage (accumul., springs)	14	3	0	2	5	0	3	0		5
-Control elements (non electrical)	6	13	2	4	3	1	0	1		13
-Actuators and damping device	19	7	2	3	3	0	0	1		7
-Mechanical transmission	6	10	0	0	0	0	0	0		2
4. Others	7	9	0	3	1	0	0	2		10

Table 8.5.5 : Correlation between sub-assemblies responsible for the failure and the causes of the minor failures
(Number of failures)

	Minor failure causes									
	Design	Manufacture	Inadequate instruction for erection	Incorrect erection	Incorrect operation	Incorrect maintenance	Stresses beyond those specified	Other external causes	Other	
Relevant test procedure:	Type tests	Routine tests	On-site tests	On-site tests	---	Checks	---	---	---	
Total number of answers:	802	1263	57	231	147	86	59	215	384	
1. Components at service voltage										
-Making and breaking units	110	96	3	9	0	4	11	15	60	
-Auxiliary interrupters and resistors	7	6	0	0	0	0	1	3	2	
-Main insulation to earth	277	265	2	28	14	11	0	30	57	
2. Electrical control and aux. circuits										
-Tripping and closing circuits	5	13	0	7	6	2	5	7	3	
-Auxiliary switches and ass. drives	10	17	1	3	11	1	1	11	13	
-Contactors relays heaters ...	50	60	0	3	11	1	2	18	31	
-Gas density supervision	39	169	1	21	59	4	4	26	21	
3. Operating mechanism										
-Compressor motors pumps	126	211	16	85	7	24	11	48	68	
-Energy storage (accumul., springs)	71	96	1	8	1	5	3	12	37	
-Control elements (non electrical)	42	169	16	25	27	27	2	17	54	
-Actuators and damping device	19	69	14	9	9	0	14	12	22	
-Mechanical transmission	12	12	2	4	2	4	2	3	4	
4. Others	34	77	1	29	0	3	3	13	12	

The publications of the results of the First Enquiry came up with proposals for additional and new tests and improved maintenance. Some of them have been introduced by IEC TC17 into standards, others have been rejected. The main proposals included the extension of the mechanical endurance test from 1000 to 2000 operating cycles, which was introduced by IEC TC17 into IEC 56 in 1982 and the performance of so called *Run In Tests* after production during routine testing. For the latter the opinion of the experts were very much different. The number of the proposed operating cycles varied from 100 to 500 cycles. Today's IEC rules, following IEC publication 56, state the performance of 30 operating cycles during routine testing, whereas the performance of about 50 operating cycles is a widely used practice.

A further proposal concerned the performance of a kind of requalification tests at periodic intervals after the introduction of producing a certain type of circuit-breaker. These kind of tests are not yet defined by standards. Anyway, the results of the Second Enquiry give also reasons to recommend such kind of tests, especially in the field of mechanical endurance

tests in order to control design and the manufacturing process during lifetime of a certain breaker type.

A judgement upon the value and the impact on reliability of the increase from 1000 to 2000 mechanical operating cycles in IEC 56, in the case of type testing, is very difficult. The introduction of the increase of the operating cycles into the standard took place during the same period as the breakers, concerned with the Second Enquiry, were placed into service. Therefore, the assumption, that many of the circuit-breakers under consideration in this evaluation have not yet been tested with 2000 mechanical operating cycles, is very likely to be true.

8.7 Mechanical endurance tests

The question if the number of 2000 mechanical operations during type testing is enough or not, is difficult to answer. As already mentioned in sub-chapter 8.4 the estimated number of operating cycles per year for 90% of the circuit-breakers within the population of the Second Enquiry is only about 80 cycles per year.

Table 8.7.1 : Estimated average number of operating cycles since commissioning until a major failure occurred

	Voltage classes (kV)						
	63≤V<100	100≤V<200	200≤V<300	300≤V<500	500≤V<700	700≤V	All
Average	489	356	471	646	504	125	471
10% Percentile	13	22	30	76	60	8	30
50% Percentile	198	158	250	245	250	50	218
95% Percentile	2065	1355	1169	1900	1881	240	1800

Table 8.7.2 : Estimated average number of operating cycles since commissioning until a minor failure occurred

	Voltage classes (kV)						
	63≤V<100	100≤V<200	200≤V<300	300≤V<500	500≤V<700	700≤V	All
Average	383	353	441	746	316	170	453
10% Percentile	22	21	42	30	35	120	25
50% Percentile	163	180	200	196	179	120	183
95% Percentile	1225	1182	1538	1800	909	220	1408

Table 8.4.3 also shows the estimated number of operating cycles through a lifetime of 25 years and 40 years. More than 90% of all breakers will not reach more than 2000 operating cycles in a 25 years lifetime. From such a point of view the today's IEC 56 standard value of 2000 operating cycles during mechanical endurance type test can be considered as adequate.

A further approach asks about the number of operating cycles when a failure occurred. Tables 8.7.1 and 8.7.2 give very interesting figures. For 95% of the reported major failures the failure occurred up to a number of 1800 operating cycles since placed in service. Regarding minor failures the situation is not strongly different: 95% of the reported minor failures happened before the circuit-breaker reached a number of 1410 operating cycles since placed in service.

From such a point of view, the question about the adequacy of the IEC 56 mechanical endurance test of 2000 operating cycles has to be reconsidered carefully. Obviously the question has to be reformulated: How many operating cycles have actually to be fulfilled by the manufacturer, in order to guarantee that throughout a circuit-breaker's life of 2000 operations the probability of a failure is acceptable? It is clear that such a question can only be applied to failures which are to correlate to operations of the breaker. E.g. SF6 tightness failures due to corrosion must not be considered when thinking about the number of operating cycles for mechanical endurance test.

However, one has to be careful, since the 2000 mechanical operating cycles test according to IEC Standard 56 (1987) [4], cannot be considered as a reliability test. The mechanical tests are required to be performed on a single specimen, the influence of wear must be considered and there is no procedure to continue the tests following a failure. Reliability tests require that a number of specimens are taken from a homogeneous population and the required number of operating cycles is then split between these specimens, the influence of wear is not considered to be part of the test and a clear procedure describes how to act after one or more failures. To summarise, the IEC 56 test does not permit failures while reliability tests look for failures over a considerably greater number of operations. IEC Standard 1123(1991), the replacement for IEC Publication 605-5 (1982), recommends methods to calculate the number of trials in order to establish a defined level of reliability.

When establishing criteria for reliability tests, the risks and the target failure probabilities should be de-

defined in advance. Serious consideration must be given to limitations, such as only part of all failures which occur in service are caused by operating the circuit-breaker. The collected data from the Second Enquiry may be useful in establishing target failure probabilities (Reference Appendix H, Table 9).

The mechanical endurance type test is not, therefore, effective in establishing a specified level of reliability. In particular, higher levels of reliability can not be assured simply by extending the number of operating cycles in the existing IEC 56 type test.

8.8 Conclusions

General conclusions for testing

- * Coming back to the introduction's question, if some of the reported failures in the enquiry could have been prevented by a test during development (type tests), after production (routine tests) or after erection (on-site tests), the answer is Yes! It seems to be very likely that at least a part of the failures with origin in the operating mechanism and in the auxiliary and control circuit as well as a part of the leakage failures should be preventable by adequate tests.
- * When laying emphasis on testing, then it has to be done primarily during type and routine testing. Special attention should be drawn to requalification testing.
- * A test never impacts or improves reliability directly. The usefulness of a test is in the possibility of revealing critical components or failure modes or even to assess appropriate maintenance criteria. Tests have mainly to control design and manufacturing process leading to the assessment of the operating limits and the consequent relevant maintenance actions. This means in other words, tests have to be considered as an auxiliary method to support design and manufacture, of which quality, and thus reliability, has to be integrated part.
- * A further investigation is necessary to define how to deal with the elements that are customer specific, to define the acceptable state of the circuit-breaker after the test and to define the necessary maintenance after the test.
- * When drawing conclusions about testing, one should always be aware of effects not yet known as

an outcome of the enquiry, such as the influence of age (the average exposure time of the involved circuit-breakers is less than 6 years and the maximum is 14 years), and such as the practice of testing beyond IEC specifications.

Conclusions for type testing

- * The overwhelming majority of failures has to be appointed to sub-assemblies and components which, during test procedures, are mainly stressed and qualified by mechanical and climate tests. Thus, most emphasis has to be laid on mechanical and climate test duties. Certainly some of them have to be reconsidered by IEC TC17 as regards improvement of their sensitivity of failure detecting potential.
- * Power testing as well as dielectric testing are stressing and qualifying some particular sub-assemblies very strong. The enquiry's data show that these sub-assemblies take responsibility for only a minor part of all failures. Thus, the today's state of the art in power and dielectric testing is successful enough and indicates no need for change or modification.
- * Temperature rise testing is absolutely uncritical. Fails to carry the current has been detected in not more than 3 cases under the responsibility of the making and breaking unit. Thus, there is no need for changes in standards.
- * Although mechanical and climate testing turn out to be the most critical ones, changes in mechanical and climate testing procedures have to be considered very carefully. Some possible approaches of improvement are, more severe tightness tests, and requalification tests by repeating mechanical endurance. Climate type testing in IEC 56 is not mandatory yet. However, the IEC procedure of low and high temperature testing is rather well proved and should be a basis for further considerations within IEC TC 17.
- * The commonly reached number of switching operations in service, being low, does not immediately support an increase of the number of operations during mechanical endurance tests. In spite of that, most of the failures in service happened before the breakers reached 2000 operations. Therefore further studies on that subject are recommended. They should be done on a carefully evaluated statistical basis. For the today's practice concerning me-

chanical endurance tests, special attention should be given to the state of the circuit-breaker after the test.

- * Life cycle testing is not yet defined in standards. However, the results of the Second Enquiry give several reasons to think in future about combination of different test duties in order to simulate stresses during life time. Life cycle testing must not be a separate testing block, but could be the last part of the type testing procedure. Recommendations for life cycle testing can not be given without further intensive studies.
- * For future systems it will be necessary, that apart from the normal dielectric and high power tests, also specific EMC-tests are done to verify the compatibility of the (micro)electronic circuits.

Conclusions for routine testing

- * As the number of leakages in both the SF₆-gas system and the hydraulic oil system have revealed to be high, it is important to improve the routine tests in these fields. Furthermore the number of faults in the operating mechanism and the electric control and auxiliary circuits push forward the thought that also in these fields the routine tests and the quality system as a whole could be improved.
- * Regarding dielectric tests, the same conclusions as for the type testing can be drawn: Dielectric testing is well proved, successful and does not need any change.

Conclusions for on-site testing

- * As on-site testing is often not trivial (measuring equipment, application of sensors etc.) and the amount of failures due to erection is not really critical no need for an improvement of existing tests or even additional tests can be derived from the Second Enquiry data.

Conclusions for requalification testing

- * As already stated above, special attention should be drawn to that particular kind of testing. The repetition rate of such tests will have to be discussed, however a periodic interval of about five years is a first proposal.
- * A requalification test should consist of the most critical test duties, which could mean mechanical endurance and probably also some climate test duties.

9. RELIABILITY DATA FOR USE IN SUBSTATION AND SYSTEM STUDIES

Preliminary and final results of the Second International Enquiry on the reliability of circuit-breakers in service have been published in two reports of CIGRE WG 13.06. The first report with preliminary results has been discussed at the CIGRE Symposium on system reliability studies in Montreal in 1991 [7]. The second report, based on the final results of the second enquiry is presented at the CIGRE Session in Paris in 1994 [10].

The second report is attached as appendix H.

10. SPECIAL ITEMS

Other topics like the contribution of low temperatures on the failure rates, the reliability of the control circuits, the conclusions to be drawn from the electrical breakdown failure rates and the number of fires and/or explosions, will be covered in this chapter.

10.1 Low temperatures

The results of the Second International Enquiry show that ambient temperatures below -5°C contribute to the failures and defects in the case of 5 major failures and 13 minor failures only.

The failures due to ambient temperatures below -5°C have been reported from 7 countries, comprising 17657 circuit-breaker-years. Many circuit-breakers in those countries were not exposed to low temperatures for significant periods of time. Therefore it is not possible to calculate failure rates. For these countries the number of failures concerning temperatures below -5°C are presented in Table 10.1.1.

Even in the countries where low temperatures are presumed having contributed to failures, the number of failures are relatively low. This may be due to the fact that the frequency of operation in these conditions is low, no lightning impulses occur and that maintenance is avoided as far as possible. Therefore it can be concluded, that the influence of low ambient temperatures on circuit-breaker failures or defects is small.

10.2 Reliability of control circuits

With 24.5% of the major failures, the origin *Electrical (control and auxiliary circuits)* is the second largest origin of the failures as in the First Enquiry. Looking for the sub-assemblies responsible for the failure, then again *Electrical control and auxiliary circuits* is the second largest category with 29%. A distinction should be made between the *Electrical control circuits* and the *Electrical auxiliary circuits*. According to the same tables, both the electrical and the mechanical control elements them self are responsible for each 10% of the major failures.

From the point of view of the characteristic of the failures, the results of the Second International Enquiry reveal that half of the failures *Does not open or close on command* originate in *Electrical (control and auxiliary circuits)*. One fifth of the *Locking failures* have the same origin. However, the electrical control circuit itself is responsible for only a third part of these failures together. This means that about 70% of the major failures with the origin *Electrical (control and auxiliary circuits)* and the failure modes *Does not open or close on command* or *Locked in open or closed position* are coming from the auxiliary circuits.

The only way defects in the electrical auxiliary circuits can interfere with the operating performance of a circuit-breaker is via the electrical control circuits. The many failures originating from the auxiliary circuits and interfering with the circuit-breakers operating performance, lead to the conclusion that there are too many interconnections between the auxiliary and the control circuits. An important source of interconnections are the interlocking and other automatic

Table 10.1.1 : Ambient temperature stress presumed contributing to the failure or defect

Ambient temperature:	$T < -25^{\circ}\text{C}$		$-25^{\circ}\text{C} \leq T < -5^{\circ}\text{C}$		$-5^{\circ}\text{C} \leq T < +5^{\circ}\text{C}$		$+5^{\circ}\text{C} \leq T < +40^{\circ}\text{C}$		$T > +40^{\circ}\text{C}$	
	(%)	No. of answers	(%)	No. of answers	(%)	No. of answers	(%)	No. of answers	(%)	No. of answers
Numbers for major failures 1)	5.0	1	20.0	4	35.0	7	40.0	8	0.0	0
Numbers for minor failures 2)	4.8	3	16.1	10	33.9	21	45.2	28	0.0	0

1) Total number of received answers for major failures: 20

2) Total number of received answers for minor failures: 62

functions (due to pole discrepancy, density of SF₆-gas, hydraulic oil pressure, etc.).

The results of the Second International Enquiry give reason to believe that a method to improve the reliability of the control circuitry is to simplify it and to reconsider the application of automatic locking and other automatic functions: Give a signal rather than automatic locking.

The electrical control circuits are an integrated part of the substations control and protection systems. The reliability performance of these systems is beyond the scope of the studies of WG 13.06. Nevertheless the results of the First and Second Enquiry are of importance for the substation and system reliability experts. Phenomena as a reduction of the reliability level due to too many secondary functions are well known for these experts. Maybe the reliability data for the modern single pressure SF₆ gas circuit-breakers encourage the substation control and protection experts to reconsider functions such as circuit-breaker back-up protection. Simplification usually results in reliability improvement.

10.3 Electrical breakdowns

Electrical breakdowns are very serious failures and deserve more attention within the survey. The number of breakdowns and the failure modes are summarized in Table 10.3.1. About 10% of the major failures appear under the characteristic *Electrical Breakdown*. The breakdown failure rate for metal enclosed equipment is comparable with that of non metal en-

closed equipment. The breakdown failure rate increases with the higher voltage ranges. The breakdown failure rate is somewhat improved compared with the data of the First Enquiry. See also the tables 2.9.8.1. and 2.9.8.2.

From the cross-correlation table *failure origin* versus *failure mode*, can be concluded that a number of electrical breakdowns have occurred at a switching operation. However, the number of severe switching duties and lightning problems are not known.

The First Enquiry teaches that the number of severe circumstances, that contributes to a failure, is limited to a few percent of all major failures.

10.4 Fires and/or explosions

Half of the electrical breakdowns result in fires and/or explosions, as can be seen from the consequences of the failures. Table 10.4.1 compares the number of major failures per failure mode with the fires and/or explosions per failure mode.

The fire and/or explosion rate does not vary much per voltage range, except for the highest voltage class, as can be seen in Table 10.4.2.

Electrical breakdowns, fires and explosions are serious failures. And although the failure rates are low, one should carefully investigate the causes of these failures and improve the reliability through design, manufacture, application, maintenance and testing as much as reasonable possible. (See also Table

Table 10.3.1 : Electrical breakdown failures and failure rates

	Second Enquiry			First Enquiry
	Metal enclosed	Non metal enclosed	Total population	Total population
Number of circuit-breaker-years:	30400	40308	70708	77892
Breakdown to earth	10	5	15	20
Breakdown between poles	5	2	7	4
Breakdown across open pole (internal)	1	16	17	31
Breakdown across open pole (external)	3	4	7	9
Total:	19	27	46	64
Failures per 10000 circuit-breaker-years:	6.3	6.7	6.5	8.2

2.9.8.3 and Table 2.9.8.4.)

10.5 Modifications of circuit-breakers

Another consequence of the major failures is the impact of such investigations for the other circuit-breakers of the same design and make.

Table 10.4.1 : Number of major failures and fire/explosions per failure mode

Characteristic (Failure mode)	Total number of major failures	Number of fire and/or explosions
Does not close on command	116	0
Does not open on command	39	1
Closes without command	5	0
Opens without command	33	0
Does not make the current	8	1
Does not break the current	14	1
Fails to carry the current	7	1
Breakdown to earth	15	2
Breakdown between poles	7	3
Breakdown across open pole (internal)	17	12
Breakdown across open pole (external)	7	5
Locked in open or closed position	134	0
Others (Intervention in 30 Minutes)	69	4
Total:	471	30

Table 10.5.1 : Number of cases in which other circuit-breakers had to be removed from service after a MF

Volatge (kV)	Number of answers	Total number of major failures
All voltages	103	475
$63 \leq V < 100$	15	67
$100 \leq V < 200$	39	160
$200 \leq V < 300$	11	89
$300 \leq V < 500$	26	120
$500 \leq V < 700$	11	35
$700 \leq V$	1	4

Removal of circuit-breaker from service for inspection or modification in order to prevent same failure

MF = Major failure

Table 10.4.2 : Circuit-breaker fire and/or explosion rates

Voltage (kV)	Metal enclosed circuit-breakers			Non metal enclosed circuit-breakers			Total population		
	Sample size (cb-years)	Number of explosions/fires	Explosions/fires per 100 cb-years	Sample size (cb-years)	Number of explosions/fires	Explosions/fires per 100 cb-years	Sample size (cb-years)	Number of explosions/fires	Explosions/fires per 100 cb-years
All voltages	30400	4	0.01	40308	27	0.07	70708	31	0.04
$63 \leq V < 100$	16186	2	0.01	8169	11	0.13	24355	13	0.05
$100 \leq V < 200$	7426	0	0.00	16094	7	0.04	23520	7	0.03
$200 \leq V < 300$	1450	1	0.07	9483	1	0.01	10933	2	0.02
$300 \leq V < 500$	4099	1	0.02	5818	3	0.05	9917	4	0.04
$500 \leq V < 700$	1236	0	0.00	659	5	0.76	1895	5	0.26
$700 \leq V$	3	0	0.00	85	0	0.00	88	0	0.00

cb = circuit-breaker

11. RECOMMENDATIONS FOR OTHER SURVEYS

In this chapter a set of recommendations for further or other surveys will be given.

11.1 Organization

It is strongly recommended for other surveys to employ the technique of local representatives in order to encourage the specialists within the utilities, to distribute the information, to communicate about preliminary results and problems, to collect and verify the questionnaires, to manage the enquiry.

The network of representatives forms also a medium to ask for separate information. The accuracy of the data depends largely upon the enthusiasm of the representative. Possibly, when treated with great care, such a network can also be used for other enquiries.

Many problems, discussed under 11.3, can be dealt with, if the organisation takes care for good instructions with very clear definitions of the items on the failure card and with examples of more complicated cases.

Another strong recommendation is to collect under separate cards the data concerning the population and the data concerning the failures.

11.2 Improvement of the population card

Additional analyses will lead to additional items on the population card. For example: the number of no load operations, the number of unloaded line/transformer operations, the number of load switchings, reactor switchings, capacitor bank switchings and short circuit current interruptions.

However, it is recommended not to make the questionnaire too complicated and to look for other ways to collect the necessary information. For example, a separate study on the number of special duties will probably result in valuable data for circuit-breaker and system reliability studies.

Another item to be considered is the collection of more detailed information on the age of the circuit

breakers in the population, in order to draw conclusions more in depth about the influence of the age on the failure rate (the so called *Bath tub curve*). Again a balance between complicated enquiry forms and the need for detailed information has to be found.

11.3 Improvement of the failure card

The terms and the subdivision used for the origin of the failure can give confusion with the identification of the sub-assembly or component responsible for the failure. The enquiry form is restricted to the components and failures of the circuit-breaker itself. This should be stated more clearly on the failure card.

The line *Compressors, motors, pumps, pipework, fittings* refer to the components in the operating mechanism and not to other pipes (density monitor)

It may be difficult to make a choice between *Design* and *Manufacture* as a cause.

It is not always easy to tick the right box. Take for example an hydraulic oil leakage, leading to locking of the circuit-breaker. The primary failure is an oil leakage, which is a minor failure. It is however discovered through the signal that the circuit-breaker has been locked. The secondary failure *Locking* is more serious and even a major failure. The failure cause, origin, characteristic, classification, identification and consequence can be different for the primary and secondary fault. Probably the operator will tick a mixture of the boxes belonging to the primary and the secondary failure.

There is large chance of confusion around the meaning of the term *Locking*. In the enquiry *Locking* has been meant the failure mode, that an alarm for the automatic blocking of the electrical or mechanical control system, has been triggered. The failure characteristic *Locked in open or closed position* is not meant for situations, where the locking is discovered, while giving a command to open or to close. In that case the failure mode *Does not open or close on command* is applicable. Also the mechanical obstruction of some part of the circuit-breaker is not meant with *Locked in open or closed position*.

The failure modes *Does not open or close on command* refer to the electrical control and mechanical operation of the circuit-breaker, while the failure modes *Does not break or make the current* refer to the more HV electrical phenomena in the interrupting units. A clarification of these terms could be necessary. Also "Fails to carry the current" is an HV electrical fault rather than the electrical control and/or mechanical operation modes *Opens or closes without command*.

Another misinterpretation can occur with a dielectric failure during a breaking operation (restrike or re-ignition). Which mode should be chosen *Does not break the current, Does not open on command, Breakdown across open pole*? Will the operator have access to enough information to fill out the failure card?

Maybe it is better to ask for the status of the circuit-breaker at the moment of the major failure. For example: in closed position, at a closing operation, at an opening operation.

Clear instructions are necessary for the defects and failures related with leakages of the SF₆-gas system, including the density monitor.

Although the definitions for downtime and time to obtain spare parts seem to be clear the results from the enquiry give reason to believe that the definitions do not cover every situation. For example in many cases the time to obtain spare parts was longer than the downtime.

11.4 Importance of statistics

It is important to inform the potential participants about the objectives of such an enquiry. The specialists within the utilities are neither always and completely informed about the necessity of particular information, nor see enough feedback from such large jobs as the collection and analysis of survey data.

More in general, utilities should pay more attention to the need for reliability criteria and methods to measure the reliability. The reliability and availability studies are not restricted to the complete grid or parts of the grid, but have to consider also the components and even the sub-components.

As a matter of fact most transmission departments within the utilities are facing the task to sell reliability rather than energy.

Therefore the collection and analysis of data and the application of statistical techniques is a must. WG 13.06 has contributed to several symposia and sessions with various points of view, in order to draw attention to its own results and to the necessity of a firm statistical failure analysis to support decisions to be made for certain developments and strategies.

12. MAIN RESULTS AND CONCLUSIONS

The Second International Enquiry concerning 70708 circuit-breaker-years of single pressure SF₆ gas circuit-breakers with a rated voltage of 72.5 kV and above (including circuit-breakers applied at service voltages of 63 kV and above) and belonging to 132 utilities from 22 countries gave the following results, conclusions and answers to the questions put forward as objectives of the survey:

Improvement in reliability

- * For the whole population the major failure rate is 0.67 failures per 100 circuit-breaker years and the minor failure rate is 4.75 failures per 100 circuit-breaker years. A further statistical analysis shows that the major failure rate varies between 0.8 ± 0.2 failures per 100 circuit-breaker years if effects like completeness, homogeneity, confidence limits and accuracy are considered.
- * The major failure rate of single pressure SF₆ circuit-breakers as results from the Second Enquiry is about 40% of the major failure rate of all technology circuit-breakers as resulted from the First Enquiry. The minor failure rate has about 30% increased with respect to the level of the First Enquiry. The reasons for this increase are possibly the SF₆ gas tightness problems, the larger number of signals per modern circuit-breaker and the better response to the questionnaire.
- * The major failure rate increases rapidly with voltages (from 0.28 to 4.55 per 100 circuit-breaker years), but in comparison with the results of the First Enquiry the improvement in the higher voltage ranges is much greater, due to changed designs.

Improvement in mechanical reliability

- * As with the First Enquiry a large part of the major failures have a mechanical origin. 44% of the major failures are of a mechanical origin in the operating mechanism; 10% mechanical in the other parts and 7% in the tightness of the SF₆ gas system. 25% of the major failures have an electrical origin in the control and auxiliary circuits.
- * 39% of the minor failures show to have a mechanical origin in the operating mechanism and 10% a mechanical origin in other parts. 40% of the minor

failures have the tightness of the SF₆ gas system as an origin. An electrical origin in the control and auxiliary circuits counts for 10% of the minor failures and the electrical origin in the main circuits for 1%.

Improvement in the reliability of mechanical operations

- * The operating mechanism and the electrical control and auxiliary circuits are the circuit-breakers components responsible for the majority of both major failures and minor failures. The dominant major failure modes are *Does not open or close on command* and *Locked in open or closed position*. If the failure mode *Others* is disregarded, these failure modes add up to 70% of the major failures, as in the First International Enquiry.

Changes in interval between overhaul and labour effort

- * The average interval between scheduled overhaul is 8.3 years. In the opinion of the experts of WG 13.06 the time between scheduled overhaul could, in many cases, be extended. Moreover, although the number of failures due to incorrect maintenance has decreased, there is still room for improvement in this area.
- * The estimated average labour cost for scheduled overhaul shows a wide variation between the 10% and 90% percentiles, typically as much as 6 to 1 and more. There is an even wider range for the estimated cost of spare parts consumed. Similar results were seen from the First Enquiry. There would therefore appear to be significant differences in policy between the utilities responding. For this reason, and also because the way in which the data has been collected and analysed, in many cases, is not statistically rigorous, the results may have limited accuracy. However, it is probably reasonable to consider the general trends arising from the data, which show that the average cost of labour effort for scheduled overhaul has reduced by 40% and the average cost of spare parts consumed for scheduled overhaul has reduced by 50%, in both cases in comparison with equivalent results from the First Enquiry.

Failure rates due to incorrect maintenance

- * The major failure rate for failures or defects reported as having incorrect maintenance as the cause has shown a significant improvement when comparing the results of the First and the Second Enquiry with a reduction of 85%. However, a similar comparison of minor failures shows a 26% decrease.
- * About a quarter of the failures are caused by inadequate instructions and incorrect erection, operation and maintenance. Better information, instructions and experience should lead to reductions in these failure causes.

Failure rates per type of operating mechanism

- * The major failure rates due to a mechanical origin in the operating mechanism is for all type of drives about the same. Most of the minor failures are either hydraulic oil or air leakages (hydraulic and pneumatic drives) or a change of the functional characteristic (spring drives), while the ratio between the minor failure rates of spring, pneumatic and hydraulic drive systems is 1:2:7, respectively.

Failure rates depending on the period of installation

- * The major failure rate shows a small increase for the circuit-breakers placed in service after 1.1.83 (ages 0 to 9 years) compared to those placed in service between 1.1.78 and 1.1.83 (ages 5 to 14 years); however this difference is not significant from a statistical point of view. The minor failure rate shows a small decrease when the same periods are compared, though once again this is not significant statistically. While the periods chosen for comparison, when the questionnaire was prepared, do not allow confirmation of the influence of the *Infant mortality* part of the *Bath tub curve* model of lifetime failures, in the opinion of the experts of WG 13.06 it is likely that *Infant mortality* had some influence on the failure rates for the later period. We could therefore propose the unconfirmed conclusion that the reliability of circuit-breakers placed in service after 1.1.83 shows improvement compared with those placed in service in the earlier period.

Failure rates depending on the location indoor or outdoor

- * The major failure rate for outdoor installed circuit-

breakers is about 1.7 times higher compared to that of indoor installed circuit-breakers. The minor failure rate for outdoor installations is about 1.6 times higher than that of indoor installations.

Failure rates depending on enclosure

- * In general non metal enclosed circuit-breakers show a major failure rate of about three times that of metal enclosed types. The situation concerning the failure rates changes substantially when the calculations are done, excluding the countries having the lowest and the highest population. In this case no difference in failure rates appears between metal enclosed and non metal enclosed.
- * The electrical breakdown failure rate is the same for metal enclosed and non metal enclosed circuit-breakers: 0.065 per 100 circuit-breaker-years; i.e. 10% of the major failure rate.

New specifications for the IEC-standards

- * It has not been investigated in which way the circuit-breakers included in this enquiry have been type tested and routine tested before delivery. It also has to be stated that some circuit-breakers are designed and manufactured according to the ANSI-standards.
- * Regarding the recommendations for new or modified IEC-standards, the results of the Second International Enquiry lead to a more severe type and routine testing of the SF₆-gas tightness, the density monitor, the operating mechanism and the electrical control and auxiliary circuits. Thinking about type testing, climate tests, mechanical tests, requalification and life cycle tests should be considered. During routine testing more attention should be paid to tightness checks (SF₆-gas as well as hydraulic oil), to testing of the operating mechanism and to testing of electrical control and auxiliary functions.
- * From the results of the enquiry neither reasons to encourage more severe dielectric or power testing, nor a basis to introduce electrical endurance testing can be found, as no information has been collected on the related stresses in service.
- * Special attention is asked for new technology devices for control and monitoring functions, as adequate EMC-testing, functional testing and testing in order to collect the data for the diagnostic tools will become necessary. Another point of attention is the identification of the secondary system, com-

ponents and software that have been subjected to all kinds of type testing.

Data for system planning studies

- * For System and Substation Reliability Studies failure mode data and probabilities of not responding properly to commands to open or close are given. The probabilities were a factor 3.7 lower in the Second Enquiry compared with the First Enquiry.
- * The lower failure rates of modern circuit-breakers may influence both the primary plant configuration and the secondary systems.
- * The median of the distribution of the estimated numbers of operating cycles per year is 30; the average is 42 and the 90% percentile is 76. This means that for most circuit-breakers after 25 years of service the number of operating cycles is less than 1900 and after 40 years less than 3040. If reliability testing is desired, use can be made of IEC 1123 [12] and the statistical data from the Second International Enquiry.
- * Improved access to spare parts of modern SF₆ gas circuit-breakers could significantly improve the circuit-breakers availability. Approximately 64% of the average downtime (95 hours per major failure) can be attributed to time to obtain spare parts.

Conclusions on diagnostic techniques

- * Improvements in diagnostic techniques (i.e. inspection, diagnostic testing and monitoring techniques) have to address the mechanical operating mechanism, the electrical control and auxiliary circuits and the SF₆ gas tightness.
- * Most important parameter to monitor is the SF₆ gas density. Other important parameters to monitor are those of the operating mechanism.
- * New technologies utilised in the circuit-breakers auxiliary and control circuits require to be developed with great care and special attention has to be given to reliability studies on the control func-

tions. New test routines have to be introduced for new devices. Close cooperation of circuit-breaker specialists with the experts involved in the fields of protection and substation control is recommended.

- * Before the development and application of sophisticated diagnostic techniques, users and manufacturers should consider the objectives they want to reach in terms of reliability, maintenance and costs. These objectives should be based on service experience.
- * The many failures originating from the auxiliary circuits and interfering with the circuit-breakers operating performance, lead to the conclusion that there are too many interconnections between the auxiliary and the control circuits. The results of the Second International Enquiry give reason to believe that a method to improve the reliability of the control circuits is to simplify them and to reconsider the application of automatic locking and other automatic functions.

General conclusions

- * The use of common definitions and questionnaires for reliability studies and maintenance techniques has to be encouraged in order to collect comparable data on a worldwide basis. IEC 1208 (1992) should be upgraded to a standard after the three years trial period.
- * In case of failure and defects the user should make a failure report and should inform the manufacturer by stating the special circumstances and measures taken. Depending upon the nature of the failure an analysis of the failure should be made in collaboration with the manufacturer. (Taken from IEC 17A(Secretariat)396 and 17C(Secretariat)138, which is a draft for a new edition of IEC 694.)
- * Results of mechanical testing concerned with the assessment of the probability that a mechanical failure can occur should be considered as a request to the circuit-breaker manufacturer.

13. ACKNOWLEDGEMENT

The authors wish to thank all utilities having participated in the enquiry. They wish to thank especially ENEL for providing the opportunity to carry out such important work.

They are grateful for the support from Study Committee 13 and especially the past Chairman Mr. E. Ruoss and the Chairman Dr. H. H. Schramm.

Lastly the authors wish to express their gratitude to Mr. E. Colombo (ENEL) for his valuable contribution in the data processing.

14. REFERENCES

- [1] **G.Mazza, R.Michaca**
The First International Enquiry on Circuit-Breaker Failures and Defects in Service.
Electra No. 79, December 1981, pp.21-91
- [2] **J.Beierer, R.Kearsley, J.Verdon**
Maintenance of Modern High Voltage Circuit-Breakers.
Electra No. 102, October 1985, pp.119-131
- [3] **R.Michaca, C.R.Heising, G.Koppl**
Summary of CIGRE Working Group 13.06 Studies on the Test and Control Methods intended to assure the Reliability of High Voltage Circuit-Breakers.
Electra No. 102, October 1985, pp.133-175
- [4] **IEC Standard 56 (1987)**
High-voltage alternating-current circuit-breakers.
- [5] **IEC Technical Report 1208 (1992)**
High-voltage alternating current circuit-breakers -
Guide for maintenance.
- [6] **A.Bargigia, C.R.Heising, A.L.J.Janssen, J.Maaskola, R.Michaca**
Interim Report on the Second International Enquiry on the Reliability of High Voltage Single Pressure SF₆ Circuit-Breakers.
CIGRE Session 1990, 23-107
- [7] **A.Bargigia, W.Degen, C.R.Heising, M.Ishikawa, A.L.J.Janssen, J.E.Maaskola, R.Michaca, M.Tudrej**
High Voltage Circuit-Breaker Reliability Data for System Reliability Studies - Interim Report CIGRE 13.06 Working Group.
CIGRE Symposium Montreal 1991, 2-01
- [8] **A.L.J.Janssen, W.Degen, M.Tudrej, S.Ikeda**
Application of Diagnostic Techniques for High Voltage Circuit-Breakers.
CIGRE Session 1992, 13-101
- [9] **A.L.J.Janssen, W.Degen, M.Tudrej, S.Ikeda**
Diagnostic Techniques for High Voltage Circuit-Breakers and their Application.
CIGRE Symposium Berlin 1993, 120-07
- [10] **C.R.Heising, E.Colombo, A.L.J.Janssen, J.E.Maaskola, E.Dialynas**
Final Report on High-Voltage Circuit-Breaker Reliability Data for Use in Substation and System Studies. (Report on Behalf of WG 13.06)
CIGRE Session 1994 13-201
- [11] **A.L.J.Janssen, W.Degen, Ch.R.Heising, H.Bruvik, E.Colombo, W.Lanz, P.Fletcher, G.Sanchis**
A Summary of the Final Results and Conclusions of the Second International Enquiry on the Reliability of High Voltage Circuit-Breakers.
CIGRE Session 1994, 13-202
- [12] **IEC Standard 1123 (1991)**
Reliability Testing. Compliance test plans for success ratio.
Remark: *Standard 1123 replaced IEC Publication 605-5 (1982): Part 5: Compliance test plans for success ratio.*
- [13] **IEC Standard 694 (1980)**
Common clauses for high-voltage switchgear and controlgear standards.
- [14] **IEC Standard 517 (1990)**
Gas-insulated metal-enclosed switchgear for rated voltages of 72.5 kV and above.
- [15] **IEC Standard 50 (191) (1990)**
International Electrotechnical Vocabulary Chapter 191 : Dependability and quality of service.
- [16] **IEC Publication 605-4 (1986)**
Equipment reliability testing
Part 4: Procedures for determining point estimates and confidence limits from equipment reliability determination tests.

15. APPENDICES

	Page:
15.1 Appendix A	131
Part one of the questionnaire: 13-88(WG06)02; i.e. the population card	
15.2 Appendix B	133
Part two of the questionnaire: 13-88(WG06)03; i.e. the failure card	
15.3 Appendix C	135
Definitions	
15.4 Appendix D	137
List of participating utilities	
15.5 Appendix E	141
A summary of the Final Results and Conclusions of the Second International Enquiry on the Reliability of High Voltage Circuit-Breakers [11]	
15.6 Appendix F	153
Application of Diagnostic Techniques for High Voltage Circuit-Breakers [8]	
15.7 Appendix G	163
Diagnostic Techniques for High Voltage Circuit-Breakers and their Ap- plication [9]	
15.8 Appendix H	171
Final report on High-Voltage Circuit- Breaker Reliability Data for Use in Substation and System Studies [10]	

DEFINITION OF OVERHAUL

Work done with the objective of repairing or replacing parts which are found to be below standard by inspection or test or as required by manufacturer's manual, in order to restore the component and/or the circuit-breaker to an acceptable condition.

EXPLANATIONSKIND OF OPERATING MECHANISM

- A : Hydraulic mechanism, which may include springs.
- B : Pneumatic mechanism, which may include springs.
- C : Spring operated mechanism.
- D : Other kind of mechanism.

COST OF SPARE PARTS

The average cost of spare parts consumed for scheduled overhaul per circuit-breaker per year should be converted into manhours using the following formula :

$$M = \frac{C + OH}{L}$$

where :

- C is the average cost (in local currency) for scheduled overhaul of spare parts consumed per circuit-breaker per year.
- OH is the overhead (in local currency) for scheduled overhaul per circuit-breaker per year that is directly associated with the storage of spare parts.
- L is the labour rate (in local currency) per manhour. Do not include overhead, except for items considered part of the direct labor cost.
- M is the number of manhours per circuit-breaker per year that represents the cost of spare parts consumed.

8. OTHER INFORMATION OR COMMENTS

REMARKS

- a) One card to be completed for each failure or defect
- b) Applies to circuit-breakers with rated voltage of 72.5 kV and above using pure SF₆-gas or SF₆ mixed with other gases. (Includes service voltages of 63 kV and above)
- c) This questionnaire is to be completed by the utility. It is recommended the questionnaire be sent to the manufacturer for immediate comment before being submitted to the CIGRE representative by the utility.
- d) Include all failures found after being put in service
- e) Do not include failures or defects found on circuit breakers placed in service prior to 1st Jan. 1978.
- f) Check one box per numbered question unless otherwise stated.
- g) If the box "other" is checked, explanation must be given.

DEFINITIONS

- 1 **Failure**
Lack of performance by an item of its required function or functions.
NOTE: The occurrence of a failure does not necessarily imply the presence of a defect if the stress or the stresses are beyond those specified.
- 2 **Major failure (of a circuit-breaker)**
Complete failure of a circuit-breaker which causes the lack of one or more of its fundamental functions.
NOTE: A major failure will result in an immediate change in the system operating conditions, e.g. the backup protective equipment being required to remove the fault, or will result in mandatory removal from service for non scheduled maintenance. (Intervention required within 30 minutes)
- 3 **Minor failure (of a circuit-breaker)**
Failure of a circuit-breaker other than a major failure or any failure, even complete, of a constructional element or a sub-assembly which does not cause a major failure of the circuit-breaker.
- 4 **Defect**
Imprecision in the state of an item (or inherent weakness) which can result in one or more failures of the item itself or of another item under the specific service or environmental or maintenance conditions for a stated period of time.
- 5 **Overhaul**
Work done with the objective of repairing or replacing parts, which are found to be below standard by inspection or test or as required by manufacturers maintenance manual, in order to restore the component and/or the circuit-breaker to an acceptable condition.
- 6 **Circuit-breaker downtime**
Time from the discovery of the failure until the breaker is returned to service.

(CONFIDENTIAL INFORMATION NOT TO BE SENT TO CIGRE)

Manufacturer	Type	Serial number
Substation name or identification		No. of local report
Circuit-breaker location identification		
Other information		

15.3 Appendix C DEFINITIONS

Failure

Lack of performance by an item of its required function or functions.

NOTE: The occurrence of a failure does not necessarily imply the presence of a defect if the stress or the stresses are beyond those specified.

Major failure (of a circuit-breaker)

Complete failure of a circuit-breaker which causes the lack of one or more of its fundamental functions.

NOTE: A major failure will result in an immediate change in the system operating conditions, e.g. the backup protective equipment being required to remove the fault, or will result in mandatory removal from service for non scheduled maintenance. (Intervention required within 30 minutes)

Minor failure (of a circuit-breaker)

Failure of a circuit-breaker other than a major failure or any failure, even complete, of a constructional element or a sub-assembly which does not cause a major failure of the circuit-breaker.

Defect

Imperfection in the state of an item (or inherent weakness) which can result in one or more failures of the item itself or of another item under the specific service or environmental or maintenance conditions for a stated part of time.

Overhaul

Work done with the objective of repairing or replacing parts, which are found to be below standard by inspection or test or as required by manufacturers maintenance manual, in order to restore the component and/or the circuit-breaker to an acceptable condition.

Circuit-breaker downtime

Time from the discovery of the failure until the breaker is returned to service.

Maintenance

The combination of all technical and administrative

actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function.

Diagnostic technique

All kinds of inspection, measurement and/or monitoring, without actions of dismantling, even with the circuit-breaker in service, to indicate the condition of the circuit-breaker and/or to detect abnormalities and finally to determine the optimum overhaul programme.

Inspection

Periodic examination of the principal features of the circuit-breaker without any dismantling.

NOTE: This examination is carried out by inspectors and is generally directed toward the indication of pressure gauges and/or levels of fluids, tightness, position of relays, pollution of insulated parts, but actions such as lubrication, cleaning, washing, etc. which can be carried out with the circuit-breaker in service, are included.

Diagnostic tests

Comparative tests of the characteristic parameters of a circuit-breaker to verify that it performs its functions, by measuring one or more of these parameters - carried out with sensors and data processing devices, connected temporary to the circuit-breaker - and comparing the measured values with the specified values or previously measured values, from e.g. routine tests, commissioning tests.

NOTE: The tests are normally carried out, the circuit-breaker being out of service.

Supervision, monitoring

Activity, performed either manually or automatically, intended to observe the state of an item.

NOTE: Automatic supervision may be performed internally or externally to the item.

Supervision, monitoring (of a circuit-breaker)

Automatic observation of the characteristic parameters of a circuit-breaker to verify that it performs its functions, by measuring one or more of these parameters - carried out with sensors and data processing devices, connected permanently to the circuit-breaker - and automatically comparing the measured values

Appendix C

with the specified values or previously measured values from e.g. routine tests, commissioning tests.

NOTE: Monitoring may be performed, the circuit-breaker being in service or out of service.

Continuous monitoring (of a circuit-breaker)

Monitoring in which the gathered data is transmitted continuously.

Non-continuous or periodic monitoring (of a circuit-breaker)

Monitoring in which the gathered data is transmitted non-continuously or periodically.

15.4 Appendix D

LIST OF PARTICIPATING UTILITIES**AUSTRALIA**

Electricity Commission of New South Wales (ECNSW)
 Electricity Trust of South Australia (ETSA)
 Queensland Electricity Commission (QEC)
 State Electricity Commission of Victoria (SECV)
 State Electricity Commission of Western Australia (SECWA)

AUSTRIA

Energie-Versorgung Niederösterreich Aktiengesellschaft (EVN)
 Stadtwerke Innsbruck (EWI)
 Kärntner Elektrizitäts-Aktiengesellschaft (KELAG)
 Salzburger Aktiengesellschaft für Energiewirtschaft (SAFE)
 Tiroler Wasserkraftwerke AG (TIWAG)
 Tauernkraftwerke Aktiengesellschaft (TKW)
 Österreichische Elektrizitätswirtschafts-Aktiengesellschaft / Verbundgesellschaft (VG)
 Vorarlberger Illwerke AG (VIW)
 Vorarlberger Kraftwerke Aktiengesellschaft (VKW)
 Stadtwerke Klagenfurt
 Wiener Stadtwerke - Wienstrom (WSE)

BELGIUM

Verenigde Energiebedrijven van het Scheldeland (EBES)
 ELECTRABEL
 Société Intercommunale Belge de Gaz et de l'Electricité (INTERCOM)
 INTERESCAUT N.V., Schelle
 UNERG S.A., Ixelles

BRASIL

CEB
 CEEE
 CEMAT
 CEMIG
 CESP
 COPEL
 CPFL
 ELETRONORTE
 ELETROPAULO
 ELETROSUL
 ENERSUL
 ESCELSA
 FURNAS
 LIGHT

CANADA

TRANSALTA

CZECHOSLOVAKIA

CEZ

FINLAND

Oulun Kaupungin Energialaitos
Espoon Sahko Oy
Etela Suomen Voima Oy
Hameen Sahko Oy
Helsingin Kaupungin Energialaitos
Imatran Voima Oy
Kemijoki Oy
Kymenlaakson Sahko Osakeyhtiö
Nokia Oy Paperi
Oulujoki Oy
Pahjolan Voima Oy
Paloheimo Oy
Porin Energialaitos
Tampereen Kaupungin Sahkolaitos
Teollisuuden Voima
Turun Kaupungin Sahkolaitos
Vaasan Sahko Oy
Vantaan Sahkolaitos Oy

FRANCE

Electricité de France (EDF)

GERMANY

Bayernwerk AG (BAG)
Berliner Kraft- und Licht AG (BEWAG)
Energieversorgung Schwaben (EVS)
Hamburgische Elektrizitätswerke AG (HEW)
Preussen Elektra Aktiengesellschaft (PE)
Rheinisch- Westfälisches Elektrizitätswerk AG (RWE)
Vereinigte Elektrizitätswerke Westfalen (VEW)

ITALY

Ente Nazionale Energia Elettrica (ENEL)

JAPAN

Chubu Electric Power Co.
Electric Power Development
Kansai Electric Power Co.
Shikoku Electric Power Co.
Tokyo Electric Power Co.

NETHERLANDS

Energiebedrijf Noord-Holland (NV PEN)
Electriciteitsbedrijf Zuid-Holland (NV EZH)
Delta Nutsbedrijf (DELTAN)
Energiebedrijf voor Groningen en Drenthe (NV EGD)
Energiebedrijf IJsselrij NV (IJSSELMIJ)
Energie maatschappij voor Gelderland en Flevoland (NV PGEM)
Maatschappij voor Electriciteit en Gas (NV MEGA)
Samenwerkende Electriciteits Productiebedrijven (NV SEP)
Regionale Energie maatschappij Utrecht (NV REMU)
Provinciale Noordbrabantse Energie Maatschappij (NV PNEM)

Appendix D

NEW ZEALAND
Transpower

NORWAY
Statkraft

PARAGUAY
Itaipu

RUMANIA
IDEB

SWEDEN
GBG Energi
GOLT ENER
Norrlandskraft
Sydkraft AB
Uddeholm Kraft
Vattenfall

SWITZERLAND
Elektrizitätswerk der Stadt Zürich (EWZ)
Aare-Tessin AG für Elektrizität (ATEL)
Bernische Kraftwerke AG (BKW)
Companie Vaudoise d'Electricité (CVE)
Centralschweizerische Kraftwerke (CKW)
Elektrizitätsgesellschaft Laufenburg AG (EGL)
S.A. L'énergie de l'Ouest-Suisse (EOS)
Kraftwerk Laufenburg (KWL)
Nordostschweizerische Kraftwerke AG (NOK)

UNITED KINGDOM
National Grid Company (NGC)

USA
Allegheny Power
American Electric Power
Bureau of Reclamation
Bonneville Power Administration
Boston Edison
Carolina Power & Light
Central Power & Light
Commonwealth Electric
Consolidated Edison Co. of NY
Consumers Power
Detroit Edison
Duke Power
Exxon Chemical
Florida Power
Florida Power & Light
Georgia Power
Gulf States Utilities
Houston Lighting & Power

Appendix D

Iowa Illinois Gas & Electric
Jacksonville Electric Authority
Louisiana Power & Light
Mississippi Power
New York Power Authority
Northeast Utilities
New York State Electric & Gas
Ohio Edison
Pennsylvania Power & Light
Salt River Project
Tampa Electric
Public Service Electric & Gas
Virginia Electric Power

U.S.S.R

MOE

YUGOSLAVIA

YOU

13-202

**A SUMMARY OF THE FINAL RESULTS AND CONCLUSIONS
OF THE SECOND INTERNATIONAL ENQUIRY ON THE RELIABILITY
OF HIGH VOLTAGE CIRCUIT BREAKERS**

by

A.L.J. JANSSEN* W. DEGEN C.R. HEISING H. BRUVIK E. COLOMBO
W. LANZ P. FLETCHER G. SANCHIS

Paper presented on behalf of Working Group 13.06

SUMMARY

The final results of the second international enquiry on the reliability of high voltage circuit-breakers are presented and compared with the results of the first worldwide enquiry. The second survey was limited to single pressure SF₆ gas circuit-breakers only, while the first enquiry covered all technologies.

The organisation of the second enquiry is illustrated and recommendations for further surveys are given. Information about the participation and the population, together with data on the number of operating cycles and on the overhaul, is discussed.

The failure rates are presented from a point of view of the causes, the characteristics, the origins, the subassemblies responsible and the consequences. The conclusions from special studies on the operating mechanism, the impact on testing, diagnostic techniques, maintenance, low temperatures, SF₆-gas leakage and system reliability studies are given.

At the end some general conclusions from the outcome of the second international survey and the comparison with the first enquiry, are drawn.

KEYWORDS

High Voltage Circuit-breakers, Reliability, Major Failure, minor failure, Enquiry.

INTRODUCTION

CIGRE Working Group 13.06 ("Reliability of High Voltage Circuit-Breakers") carried out worldwide reliability studies on high voltage circuit-breakers during the fifteen year period 1971 through 1985. An important part of the activities was to conduct the first international enquiry on circuit-breaker failures and defects in service. These studies are reported in three CIGRE SC 13 final reports [1], [2], [3].

The studies were the basis for new mechanical and environmental tests on circuit-breakers in the IEC standards, such as mechanical operation tests with an increased number of operations,

low and high temperature tests and humidity tests [4]. The CIGRE WG 13.06 questionnaire and definitions have been the starting point for the development of IEC-guidelines, for collecting failure data [5]. In 1986 a new CIGRE WG 13.06 was set up on "Reliability of High Voltage Circuit-Breakers" @. The scope was to obtain detailed information of circuit-breaker performance in service as well as possible measures to improve the reliability and reduce the maintenance costs. Two major tasks were undertaken:

1. Conduct a second international enquiry on the reliability of high voltage circuit-breakers in service;
2. Study the parameters for permanent supervision in service as well as relevant diagnostic methods.

The second enquiry was limited to single pressure SF₆ gas circuit-breakers, placed in service after 1 January 1978 with a rated voltage of 72.5 kV and above (including service voltages of 63 kV and above). The second enquiry has been completed and covered the period 1 January 1988 up to 31 December 1991. The second enquiry

@ All members of CIGRE WG 13.06 have contributed to the enquiry and the studies by the information they submitted and their participation in the discussions.

The present membership of CIGRE WG 13.06 is H. Bruvik (NO), E. Colombo (IT), N. Cuk (CA), E. Dialynas (GR), J. Declercq (BE), W. Degen (DE), P. Fletcher (GB), W. Franca (BR), Ch. Heising (US), A. Janssen (NL), O. Karlen (SE), J. Maaskola (SF), G. Meinders (US), W. Lanz (CH), V. Onu (RU), S. Peric (AU), G. Sanchis (FR), J. Sikula (CZ), I. Stahan (YU), E. Thuries (FR), M. Tsuchiya (JP), M. Tudrej (FR), V. Varivodov (CIS), E. Zaima (JP).

The following past members and guests also contributed to this work: A. Bargigia (IT), R. Baumgartner (CH), J. Beierer (DE), P. Botelho Neves (BR), J. Brunke (US), L. Desmoulins (FR), S. Ikeda (JP), M. Ishikawa (JP), R. Jeanjean (FR), R. Michaca (FR), D. Stevens (GB).

* KEMA High Power Laboratory - Utrechtseweg 310 - 6812 AR ARNHEM - Netherlands

included 70708 circuit-breaker-years.

The first enquiry, from 1974 through 1977, included 77892 circuit-breakers-years of all technologies. The first enquiry was limited to circuit-breakers placed in service after 1964 with a service voltage of 63 kV and above.

To date WG 13.06 has published several reports on the preliminary results of the second international enquiry [6], [7], [8]. At the symposium on Diagnostic and Maintenance Techniques in Berlin (93) some of the relevant final results have been published [9]. The final results, that are of importance for the Substation and System Reliability Studies are published at the CIGRE 1994 session [10].

A general report on the results of the second international enquiry and on the results of a number of studies on particular subjects will be published in a CIGRE Technical Brochure. The studies incorporate items such as Use of Diagnostics, Maintenance Policy, System Reliability Study Data, Kind of Operating Mechanism, Comparison of Metal Enclosed versus Non-Metal Enclosed Reliability, Impact on Testing, SF₆ Gas Leakages. The Technical Brochure will be available via the CIGRE Central Office.

In the discussion of this subject, two important questions should be considered:

1. Has there been an improvement in the reliability of high voltage circuit-breakers since the first worldwide survey?
2. Are additional specifications needed in the standards?

For reason of comparison between the results of the second enquiry and the first one, the results of the latter will be put between braces {}.

The following abbreviations will be used through this report: MF major failure; mf minor failure; CB circuit-breaker; cby circuit-breaker-years; ME metal enclosed; NME non-metal enclosed; GCB single pressure SF₆ gas circuit-breaker.

OBJECTIVES

Before conducting an enquiry on the reliability of certain components, it is important to look for the objectives one wishes to reach with the results of the enquiry. The most important objectives that are considered with the second international enquiry on the reliability of high voltage circuit-breakers in service were:

1. to discover the subassemblies and specific functions of the CB that deserve more attention with respect to the improvement of quality assessment, design, testing, maintenance, diagnostics, etc;
2. to establish the reliability level of different classes of GCB (ME, NME, located indoors/outdoors, voltage range, type of operating mechanism, time in service);
3. to give information for CB-experts in order to define their policy with respect to the maintenance strategy, including diagnostics, and with respect to the retrofit or replacement of the old CB's;
4. to gather data for substation and system reliability studies.

Other objectives are to compare the results with those of the first enquiry, to give clear definitions for certain reliability and maintenance terms and to encourage the cooperation between user and manufacturer in the field of reliability information.

SCOPE

The most important reason to establish a new Working Group on the reliability of HV CB's, was the idea that GCB's should have a reliability performance that is substantially improved compared with that of CB's of an older design, as the number of parts has been considerably decreased.

As a short study in 1987 revealed, most utilities are buying the GCB's and the population of this type is increasing rapidly. Besides, the number of GCB's in service was already large enough to consider a population comparable with that of the first enquiry.

Therefore the second enquiry has been limited to single pressure SF₆ gas circuit-breakers only. Circuit-breakers that use SF₆-gas mixed with other gases are considered as well.

The voltage range considered is not related to the service voltage, as in the first enquiry, but related to the rated voltage of the CB. The lower limit is chosen to be a rated voltage of 72.5 kV.

However, in order to have results comparable with the first enquiry, CB's with a service voltage of 63 kV and above are included.

The enquiry and the studies are restricted to failures and defects that occur in the CB itself. The enquiry does not consider failures and defects in the auxiliary equipment and wiring that can not be regarded as an integral part of that particular CB.

DEFINITIONS

The definitions for reliability and failures are the same as for the first enquiry [1]. However, the single exception is that the list of major failures has been extended with the addition of the failure mode "Locked in open or closed position".

The definitions for maintenance, overhaul, CB-downtime, inspection and diagnostic techniques are consistent with the definitions of IEC Technical Report 1208 [5].

For the definitions, see appendix A of [8].

ORGANIZATION

The data for the enquiry are collected by a special questionnaire, which has been designed to give the necessary information without identifying the manufacturer of the equipment involved. The questionnaire was revised to be simpler than for the first enquiry and to also explore two new areas in further depth: (1) reliability data have been collected for different types of mechanisms since this is the component with the highest failure rate (2) reliability data have been collected for two separate periods after commissioning in order to show the change of the failure rate with time in service.

The questionnaire is divided into two parts on two separate cards. The first part is concerned with general information per year for statistical analysis on the population of CB's in service for each rated voltage and for each category for which the collection of data applies. The second part of the questionnaire is concerned with the particular information on each failure recorded during the considered year. See appendix 1 and 2 of [6].

The collection of enquiry data for each country was made by a national CIGRE representative, who offered help in filling out the questionnaire. He was responsible for organising the collection of data, advising the utilities and providing a link between the utility and the data processing

centre in all questions concerning the enquiry. ENEL (the Italian Electricity Board) was responsible for the data processing. ENEL also printed the cards for the enquiry in English and French, and assumed the corresponding costs without asking any contribution. ENEL further undertook to respect the decision of WG 13.06 as regards the publication of the results. The data collected in the second enquiry will be kept confidential as was done in the first enquiry. Only general results will be published. The utility or country of origin will not be associated or identified with any of the specific data submitted.

PARTICIPATION

A total of 132 (102) utilities from 22 (22) countries answered the CIGRE questionnaires of the second enquiry during the period under consideration. The countries with between brackets the number of participating utilities are: Austria (11), Australia (5), Belgium (5), Brasil (14), Canada (1) "Czechoslovakia" (1), "Germany" (7), France (1), Finland (19), Italy (1), Japan (5), Netherlands (10), New Zealand (1), Norway (1), Paraguay (1), Rumania (1), Sweden (6), Switzerland (9), U.K. (1), U.S.A. (30), "USSR" (1) and "Yugoslavia" (1).

During the period under consideration not only reorganizations and name changes in and between utilities did take place, but also between nations, as has been indicated with the quotes.

A total of 385 population cards and 3833 failure cards are processed. The failure cards can be split up into 475 MF-cards and 3358 mf-cards. Sometimes not all categories of questions on a card were completed.

POPULATION

Figure 1 shows the distribution of the c.b. population among the participating countries; the first three countries sum up to about 68% of the whole population and the first one to 35%.

Table 1a gives the number of cby that forms the total population.

From a population of 70708 cby it can be seen that 70.0% is installed between 1.1.83 and 1.1.92; 85.2% is outdoor located; 57.0% is NME. Almost all NME CB's are located outdoors (94%), while most ME CB's are located outdoors (74%). The type of operating mechanism is split up as follows: 51.4% is hydraulic; 30.1% is pneumatic and 18.5% is spring operated.

The estimated average number of operating cycles for the whole population is summarised in table 2. The average is 42 (26.5) cycles per year and the median value is 30 (13) cycles per year. However, there is different method of weighting the response to the enquiry, as the evaluation in the first enquiry is based on every answer (i.e. group of circuit-breakers) and in the second enquiry on every circuit-breaker-year.

No information is collected on the kind of operating cycles; i.e. no load, current interruption, making/breaking a short circuit current. This applies for both the population card and the failure card.

FAILURE RATES

Table 3 shows an overview of the MF- and mf-rates in comparison with the first enquiry results. The total MF-rate (.0067 (.0158) per year) is considerably reduced since the first enquiry. But the mf-rate shows a growth (.0475 (.0355) per year). This trend is caused by the larger number of alarms that nowadays is collected at a CB, by the more accurate collection of

mf-data and by the high number of leakages of the GCR's. See also table 4.

The increase of the failure rates with higher voltages is expected from the comparable larger number of parts. However, in comparison with the results of the first enquiry the improvement of the reliability in the higher voltage ranges is much greater, due to changed designs.

Although the MF-rate shows a small increase for the circuit-breakers put into service after 1.1.83 compared to those installed between 1.1.78 and 1.1.83, this difference is not significant from a statistical point of view.

The failure rates given are relevant to the cb population of all countries participating in the enquiry. Should the data concerning the countries having the highest and lowest cb population be excluded from the statistical evaluation the failure rates would result in .01 (.024) and 0.069 (.063) failures per cby for MF and mf, respectively.

In the tables 1b and 1c the MF and mf are presented in the same way as the whole population in table 1a.

The MF-rates for ME and NME-equipment are .0032 and .0094 per cby, while for mf the rates are .022 and .067 per cby. Without the data from the countries with the highest and the lowest population, the failure rates for ME and NME equipment are equal.

From the tables can be calculated, that, for the large subpopulation of ME CB's with a rated voltage below 100 kv (16186 cby), the MF-rate is very low: .0007 per cby. The influence on the whole population and on the ME failure rate is large. Without this subpopulation the MF-rate is .0085 for the rest of the total population and .0061 for the rest of the ME CB's.

Other subpopulations do not influence the results substantially.

From similar studies the accuracy of the overall MF-rate is estimated to be up to 50%. Comparable accuracies have been found during the first enquiry [1].

SUBASSEMBLY RESPONSIBLE

The tables 4 and 5 give a division of the MF and the mf by the subassemblies responsible for the failure. In table 4 the main categories are compared with the results of the first enquiry. When comparing, one has to be aware of the high number of mechanical operating elements in the HV-heads of the older technology CB's. From the results of table 5 it is clear that the operating mechanism is the subassembly that is responsible for most of the failures. The second category is the electrical control and auxiliary circuits.

Or to say it the other way around: the interrupter units show a MF-rate that corresponds to a MTBF (mean time between failures) of 1070 years, compared with a MTBF for the whole CB of 149 years.

CHARACTERISTICS OF THE FAILURES

An important item of the failure analysis is the characteristic of the failures. The tables 6 and 7 show the MF- and mf-rates per characteristic.

Half of the MF have the characteristic "Locking in open or closed position" or "Does not close on command". A special study has been made and it is believed that approximately half of the locking failures has been detected at an open or close command. Also a few electrical breakdowns across open pole (internal) may have occurred after an operation.

Presumably some of the failures with the characteristic "Closes without command" and "Opens without command" occur shortly after an operation with command.

In the first enquiry some of the "Closed without command" were due to loss of air pressure in air blast breakers. As the air continued to drop, the breaker then "closed without command" in order to prevent "breakdown across open pole".

The electrical breakdown failure rate is .065 per 100 cby, i.e. 10% of the MF-rate. The breakdown failure rate is equal for ME and NME equipment [9].

Two third of the mf are characterized by leakages.

CAUSE AND ORIGIN OF THE FAILURES

More than half of the MF and mf is caused by the design and manufacture of the CB, as can be seen from table 8. As with the first enquiry about two third of the MF and a very large part of the mf do have a mechanical origin. 44% of all MF are of a mechanical origin in the operating mechanism; 10.4% are with a mechanical origin in other parts and 7.2% do have the tightness of the SF₆-gas-system as an origin. The other MF have electrical origins: high voltage electrical (main circuit) 13.9% and low voltage electrical (control and auxiliary system) 24.5%.

39.6% of the mf show to have the tightness of the SF₆-gas-system as an origin, while the mechanical in operating mechanism is the origin for 39.4% of the mf. The origins mechanical in other parts, high voltage electrical and low voltage electrical are 9.9%, 0.9% and 10.2%.

CONSEQUENCES OF THE MAJOR FAILURES

About a quarter of the MF lead to corrective actions to be taken in other CB's of the same design. 31 MF (i.e. 7% of the MF) lead to a fire or an explosion of the CB; 26 MF with NME CB's and 5 with ME CB's. Most of the fires and/or explosions (22) are related with electrical breakdowns:

	MF (ME/NME)	fire/expl.
breakdown to earth	15 10/ 5	2
between poles	7 5/ 2	3
across open pole (int.)	17 1/16	12
across open pole (ext.)	7 3/ 4	5

4 other fires and/or explosions are related with the modes "Does not open on command", "Does not make the current", "Does not break the current" and "Fails to carry the current". The remaining 5 fires/explosions are related with the characteristic "Other".

As stated before, from the questionnaires it is not possible to correlate the number of electrical breakdowns and explosions to the more severe current interruptions.

Another consequence of the MF is the CB outage time, that will be covered in the chapter on System Reliability Studies [10].

OPERATING MECHANISM

The number of MF and mf of the origin "Mechanical in Operating Mechanism" indicates very clearly the impact of the operating mechanism on the CB reliability.

The distribution of the different operating mechanisms is given in table 1. More than half of the number of CB's have an hydraulic operating mechanism. 25 % of all CB's with a rated voltage less than 200 kv use a spring operating mechanism. Above 200 kv less than 5 % use spring

mechanisms, but 70 % use hydraulic mechanisms.

Per type of drive system, table 9 shows the failure rates with the origin "Mechanical in Operating Mechanism". As most CB's below 200 kv will be equipped with a single drive system, the failure rates are also presented for voltages above and below 200 kv.

The different types of operating mechanisms have significant differences in their failure modes. The highest risk of a MF in a hydraulic or pneumatic drive is "locked in open or closed position", while the highest risk for spring driven CB's is the failure mode "does not open or close on command". Most of the mf are either hydraulic oil or air leakages (hydraulic and pneumatic drives) or a change of the functional characteristics (spring drives).

IMPACT ON TESTING

Reliability, as a result of an high quality level, is not restricted to the testing of an equipment or an apparatus; it must be an integrated part of the design/development process and of the manufacturing process as well. The aim of studying the second enquiry's data regarding the impact on testing is to reveal critical subassemblies, critical failure modes and failure causes in order to relate them to adequate test procedures.

When asking about the distribution of the failure causes, "Design" and "Manufacture" are obvious to be the critical ones.

Emphasis should be laid on type and routine testing, in order to reveal design and manufacturing failures. See table 8.

In the tables 5 and 6 the operating mechanism is a very critical sub-assembly and the modes "Does not close on command" and "Locking in open or closed position" are the critical ones, whereas for mf the tightness problem - both hydraulic oil and SF₆-gas - turns out to be the largest one.

Therefore, during type testing most emphasis has to be laid on mechanical and climate tests, whereas power- and dielectric testing as well as temperature rise testing of todays practice seem successful enough. However, one should be aware of effects not yet known, such as the effect of age (as the average exposure time of the involved CB's is less than 6 years and the maximum is 14 years) and such as the practice of testing beyond IEC specifications. Moreover, the seriousness of the interrupting and breakdown failures has also to be taken into consideration.

Qualification tests in the sense of a periodical repetition of a mechanical endurance test on a certain breaker type should be considered carefully in the future, in order to keep an high level of quality over the whole manufacturing period.

DIAGNOSTIC TECHNIQUES

WG 13.06 has published two reports on diagnostic techniques for CB's [8],[9]. The first report is dealing with the more general aspects, such as definitions, objectives, reliability, policy of the utilities, testing of monitors and the integration with other secondary systems. The other report draws conclusions on the basis of the results of the second international enquiry and compares these results with developments as described in the literature.

The conclusions from the studies of WG 13.06 are:

- * the most important parameter to monitor is the SF₆-gas-density;
- * other important parameters to monitor are those of the operating mechanism;
- * it is recommended to improve the reliability of the electrical control and auxiliary circuits;
- * before the development and the application of diagnostic techniques users and manufacturers should consider the objectives they want to reach in terms of reliability and costs.

MAINTENANCE

Table 10 summarizes the responses to questions on the average interval between scheduled overhaul, average labour effort for scheduled overhaul and cost of spare parts for scheduled overhaul. The results of the first enquiry are also shown. Although not directly comparable, due to the different definitions of overhaul/servicing the comparison can be used as an indication of trends.

The average estimated interval between scheduled maintenance is 8.3 (2.1) years. Average estimated labour effort is 23.8 (38.6) man-hours per year and the average costs of spare parts 38.1 (67.6) man-hours per year. Spare parts costs were measured in man-hours to avoid problems in converting from local currency.

Responses showed that labour effort increased with increasing voltage and that indoor CB's require half the effort of outdoor. They also showed that the costs of spare parts for NME CB's is about half the average and for outdoor ME CB's double the average.

In the opinion of the experts within WG 13.06 the time between scheduled overhaul could, in many cases, be extended.

Only 6.1% (4.7%) of the MF and 13.7% (25.1%) of the mf were found during maintenance. These figures would indicate that maintenance is not very effective in finding defects responsible for failures. On the other hand 2.8% (8.1%) of the MF and 2.6% (4.5%) of the mf were attributed to incorrect maintenance. Although significantly better than the results of the first enquiry, there is still room for improvement in this area.

LOW TEMPERATURES

Failures due to ambient temperatures below -5 C have been reported from 7 countries, comprising 17657 cby. The 5 MF and 13 mf result in very low failure rates: 4 % of the overall MF-rate and 2 % of the mf-rate.

SF₆-LEAKAGE

Only 7% of the MF have the origin "tightness of SF₆ gas-system", because of the continuous monitoring techniques. On the other hand 40% of the mf originate from tightness problems.

In fact, the SF₆ failure rates must be considered as minimum values for the real behaviour of SF₆ gas-tightness, as a special questionnaire about the practice of each country shows that in the second international enquiry, not every alarm on SF₆ density has been reported.

A special study on SF₆ gas tightness has lead to the following conclusions:

- * the SF₆ gas tightness failure rate is at least .02 per cby;
- * the tightness of the CB with a rated voltage below 100 kv is better;

- * the tightness of ME CB's is better than that of NME CB's;
- * the tightness of NME CB's is better for those located indoors;
- * the tightness problems with NME CB's installed between 1.1.78 and 1.1.83 are twice the failure rate of those installed between 1.1.83 and 1.1.92;
- * the tightness of indoor CB is better than for those located outdoor;
- * design and manufacture are the main causes for these failures;
- * the main characteristics are "locking" and "opens without command";
- * further development is needed to improve both the SF₆ gas tightness and the density monitor.

SYSTEM RELIABILITY STUDIES

The data for use in substation and system reliability studies are given in [10]. This includes both the MF-rate and the CB downtime at each of different voltage ranges. A MF is equivalent to a forced outage. Two important contributions to the knowledge of CB reliability are: (1) the failure mode data, and (2) the calculation of probabilities of not responding properly to a command to open or to close. The average number of CB operating cycles per year were used to calculate these probabilities.

For GCB's approximately 64% of the average downtime (95 hours per MF) can be attributed to "time to obtain spare parts". Improved access to spare parts could significantly improve the CB availability.

The data on CB failure modes and failure probabilities will enable better models to be developed. Better data and better models have both been needed in order to improve the credibility of these studies. The data from the second enquiry can be used for SF₆ single pressure CB's, and the data from the first enquiry can be used for older technology CB's.

GENERAL CONCLUSIONS

The main objectives of the second international enquiry concerning 70708 circuit-breaker-years for single pressure SF₆-gas circuit-breakers with a rated voltage of 72.5 kv and above (including circuit-breakers applied at system voltages of 63 kv and above) and belonging to 132 utilities from 22 countries, are reached. The principal conclusions are as follows:

- * The MF-rate of modern SF₆ CB's is .0067 per cby and is about 60% lower compared with the MF-rate of all technologies;
- * The mf-rate of modern SF₆ CB's is .0475 per cby and is about 30% higher than that of the first enquiry. Some of the possible reasons may be the better response to the survey, the larger number of signals per CB and the SF₆ leakage problems;
- * The operating mechanism is the subassembly with the most failures. The dominant failure modes are "Does not open or close on command" and "Locked in open or closed position";

From further analysis the following conclusions can be drawn:

- * from the analysis of the subassemblies responsible and the characteristics of the failures, it can be concluded that there is a strong need to simplify the electrical and mechanical control process. A reconsideration of the advantages and disadvantages of locking and other automatic func-

tions versus alarm is recommended for both the CB- and the substation-design (CB-back-up protection);

- * The MF- and mf-rates related to SF6-gas-tightness including the density monitor are substantial. A further improvement is necessary with respect to the tightness design, the density monitoring and the testing of tightness;
- * Additional type tests and requalification tests for mechanical endurance, climate endurance and life cycle, should be considered carefully in the future;

The experience of the second enquiry leads to recommendations for future surveys:

- * the use of common definitions for reliability studies and maintenance techniques should be encouraged;
- * the enquiry forms still need some improvement in order to avoid misunderstandings with the utilities experts. The organisation of a survey via national CIGRE representatives, who take care of the instructions, the communication, the participation and the verification, can be recommended.

More detailed information from the second international enquiry will be available in a CIGRE Technical Brochure.

REFERENCES

[1] G. Mazza, R. Michaca The first International Enquiry on Circuit-Breaker Failures and Defects in service. Electra nr. 79, december 1981, pp. 21-91

[2] J. Beierer, R. Kearsley, J. Verdon Maintenance of Modern High Voltage Circuit-Breakers. Electra nr. 102, October 1985, pp. 119-131

[3] R. Michaca, C.R. Heising, G. Koppl Summary of CIGRE Working Group 13.06 Studies on the Test and Control Methods intended to assure the Reliability of High Voltage Circuit-Breakers. Electra nr. 102, October 1985, pp. 133-175.

[4] IEC Publication 56 (1987) High voltage alternating current circuit-breakers.

[5] IEC Technical Report 1208 (1992) High voltage alternating current circuit-breakers. Guide for maintenance.

[6] A.Bargigia, C.R.Heising,A.L.J.Janssen, J.Maaskola, R.Michaca Interim Report on the Second International Enquiry on the Reliability of High Voltage Single Pressure SF6 Circuit-Breakers. CIGRE session 1990, 23-107

[7] A.Bargigia, W.Degen, C.R.Heising, M.Ishikawa, A.L.J.Janssen, J.E.Maaskola, R.Michaca, M.Tudrej High Voltage Circuit-Breaker Reliability Data for use in System Reliability Studies - Interim Report CIGRE 13.06 Working Group. CIGRE Symposium Montreal 1991, 2-01

[8] A.L.J.Janssen, W.Degen, M.Tudrej, S.Ikeda Application of Diagnostic Techniques for High Voltage Circuit-Breakers. CIGRE Session 1992, 13-101

[9] A.L.J.Janssen, W.Degen, M.Tudrej, S.Ikeda Diagnostic Techniques for High Voltage Circuit-Breakers and their Application. CIGRE Symposium Berlin 1993, 120-07

[10] C.R.Heising, E.Colombo, A.L.J.Janssen,J.E.Maaskola,E.Dialynas Final Report on High Voltage Circuit-Breakers Reliability Data for Use in Substation and System Studies (Report on Behalf of WG 13.06) CIGRE Session 1994, 13-201

Number of circuit-breaker-years

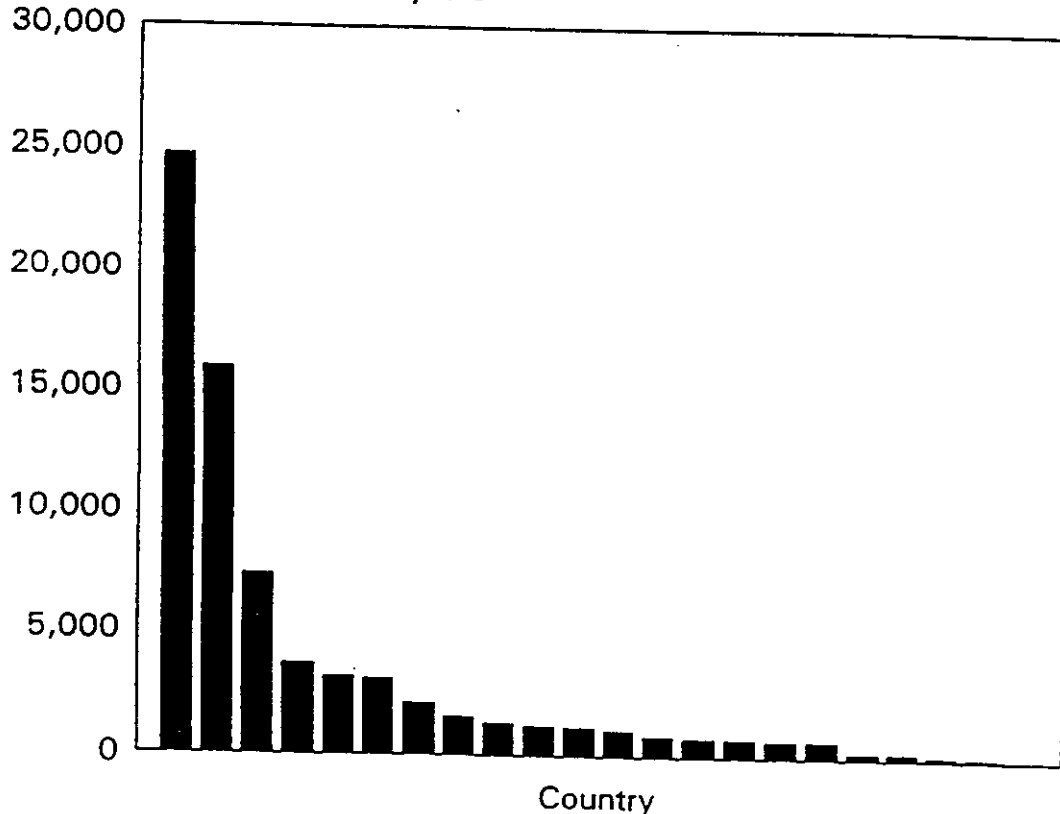


Table 1: Results of the 2nd international enquiry on the reliability of HVCB's in service of all countries for each rated voltage and for each category for which collection of data applies

Table 1a: number of circuit-breaker-years (cby)

Voltage (kV)	LOCATION INDOORS						LOCATION OUTDOORS						TOTALS
	METAL-ENCLOSED			NON METAL-ENCLOSED			METAL-ENCLOSED			NON METAL-ENCLOSED			
	A	B	C	A	B	C	A	B	C	A	B	C	
63 ≤ V < 100	694	1529	558	61	1226	198	2783	5702	4920	4991	1221	472	24355
100 ≤ V < 200	1448	1062	964	311	82	79	1079	2405	468	8210	2913	4499	23520
200 ≤ V < 300	103	143	18	110	25	0	424	735	27	7647	1402	399	10933
300 ≤ V < 500	902	347	25	260	104	9	2061	740	24	3971	1070	404	9917
500 ≤ V < 700	218	15	0	9	0	0	543	460	0	497	149	4	1895
700 ≤ V	0	0	0	0	0	0	3	0	0	57	28	0	88
SUBTOTALS	3365	3096	1565	751	1437	286	6893	10042	5439	25373	6683	5778	
TOTALS	8026			2474			22374			37834			70708

Table 1b: number of Major Failures (MF)

Voltage (kV)	LOCATION INDOORS						LOCATION OUTDOORS						TOTALS
	METAL-ENCLOSED			NON METAL-ENCLOSED			METAL-ENCLOSED			NON METAL-ENCLOSED			
	A	B	C	A	B	C	A	B	C	A	B	C	
63 ≤ V < 100	1	2	2	0	0	0	0	3	3	25	25	6	67
100 ≤ V < 200	7	1	4	1	0	0	4	9	2	72	24	36	160
200 ≤ V < 300	0	1	0	0	1	0	6	9	0	44	18	10	89
300 ≤ V < 500	11	5	0	0	0	0	11	7	0	57	16	13	120
500 ≤ V < 700	8	0	0	0	0	0	0	1	0	19	7	0	35
700 ≤ V	0	0	0	0	0	0	0	0	0	0	4	0	4
SUBTOTALS	27	9	6	1	1	0	21	29	5	217	94	65	
TOTALS	42			2			55			376			475

Table 1c: number of minor failures (mf)

Voltage (kV)	LOCATION INDOORS						LOCATION OUTDOORS						TOTALS
	METAL-ENCLOSED			NON METAL-ENCLOSED			METAL-ENCLOSED			NON METAL-ENCLOSED			
	A	B	C	A	B	C	A	B	C	A	B	C	
63 ≤ V < 100	37	7	4	3	8	0	41	36	20	349	27	10	542
100 ≤ V < 200	107	6	3	3	1	1	53	32	4	645	162	101	1118
200 ≤ V < 300	11	0	0	1	0	0	19	34	1	597	67	32	762
300 ≤ V < 500	55	7	0	1	0	0	72	21	0	508	51	55	770
500 ≤ V < 700	80	0	0	0	0	0	7	5	0	59	14	0	155
700 ≤ V	0	0	0	0	1	0	0	0	0	4	6	0	11
SUBTOTALS	290	20	7	8	10	1	192	128	25	2152	327	198	
TOTALS	317			19			345			2677			3358

A: HYDRAULIC MECHANISM, WHICH MAY INCLUDE SPRINGS
 B: PNEUMATIC MECHANISM, WHICH MAY INCLUDE SPRINGS
 C: SPRING OPERATED MECHANISM

Table 2
Estimated Average number of operating cycles per circuit-breaker-year

	1st enquiry	2nd enquiry
Average	27	42
10% percentile	3	132
25% percentile	6	20
Median	13	30
75% percentile	29	50
90% percentile	53	76
95% percentile	78	84
Maximum	549	1760

Table 3
MF- and mf-rate for each rated voltage range for the first and second enquiry
(failure per 100 circuit-breaker-years)

Voltages (kV)	Second Enquiry						First Enquiry	
	Placed in service 1.1.78-1.1.83		Placed in service after 1.1.83		all period		all period	
	MF	mf	MF	mf	MF	mf	MF	mf
all voltages	0.56	5.35	0.72	4.49	0.67	4.75	1.58	3.55
63 ≤ V < 100	0.16	1.39	0.32	2.57	0.28	2.23	0.41	1.65
100 ≤ V < 200	0.58	6.55	0.72	4.09	0.68	4.75	1.63	4.18
200 ≤ V < 300	0.83	8.28	0.81	6.35	0.81	6.97	2.59	6.39
300 ≤ V < 500	1.07	8.67	1.29	7.28	1.21	7.76	4.55	16.35
500 ≤ V < 700	0.66	3.44	2.63	11.32	1.85	8.18		
700 ≤ V	0.00*	0.00*	4.71	12.94	4.55	12.50	10.46	4.93

*Population: 3 circuit-breaker-years

Table 4
Comparison of the final data obtained from the 1st and 2nd international
enquiry on the reliability of high voltage circuit-breakers in service
(failures per 100 circuit-breaker-years)

Subassembly responsible	Major Failure rate		minor failure rate	
	1st	2nd	1st	2nd
1.Components at service voltage	.76 (48%) ^a	.14 (21%)	.92 (26%)	1.44 (31%)
2.El. control and aux. circuits	.30 (19%)	.19 (29%)	.57 (16%)	.92 (20%)
3.Operating mechanism	.52 (33%)	.29 (43%)	2.06 (58%)	2.05 (44%)
4.Others		.05 (7%)		.25 (5%)
Total failure rate	1.58 (100%)	.67 (100%)	3.55 (100%)	4.66 (100%)

^a including 20% for operating elements at service voltage, such as valves
Number of cb-years of 1st international enquiry: 77892; all technologies applied at a service voltage of 63 kV and above. Number of cb-years in 2nd international enquiry: 70708; single pressure SF₆-gas cb's at a service voltage of 63 kV and above.

Table 5
Summary of final data from 2nd international enquiry on the reliability
of high voltage SF6 single pressure circuit-breakers
(number of failures/defects per subassembly or component)

Component responsible for failures/defects	Number of Major Failures		Number of minor failures/defects	
1.Components at service voltage	99		1019	
1.1 interrupting unit	66	(14.0%)	310	(9.4%)
1.2 aux. interr., resistor	6	(1.3%)	20	(0.6%)
1.3 main insul. to earth	27	(5.7%)	689	(20.9%)
2.El. control and auxiliary circuits	137		650	
2.1 trip/close circuits	47	(10.0%)	49	(1.5%)
2.2 aux. switches	35	(7.4%)	69	(2.1%)
2.3 contactors, heaters, etc.	36	(7.6%)	178	(5.4%)
2.4 gas density monitor	19	(4.0%)	354	(10.7%)
3.Operating mechanism	204		1449	
3.1 compressors, pumps etc.	64	(13.6%)	615	(18.7%)
3.2 energy storage	36	(7.6%)	238	(7.2%)
3.3 control elements	44	(9.3%)	383	(11.6%)
3.4 actuators, damping dev.	42	(8.9%)	168	(5.1%)
3.5 mech. transmission	18	(3.8%)	45	(1.4%)
4.Others	32	(6.8%)	178	(5.4%)
Total	472	(100%)	3296	(100%)
Subassembly responsible not indicated on failure card	3		62	

Table 6
MF-rate by characteristic for the first and second enquiry

Characteristic	First enquiry		Second enquiry	
	MF per 100 cb-years		MF per 100 cb-years	
Does not close on command	.33	(33.7%)	.164	(24.6%)
Does not open on command	.14	(14.1%)	.055	(8.3%)
Closes without command	.02	(1.7%)	.007	(1.0%)
Opens without command	.05	(5.2%)	.047	(7.0%)
Does not make the current	.02	(1.6%)	.011	(1.7%)
Does not break the current	.02	(1.9%)	.020	(2.9%)
Fails to carry current	.02	(2.5%)	.010	(1.5%)
Breakdown to earth	.03	(2.6%)	.021	(3.2%)
Breakdown between poles	.00	(0.5%)	.010	(1.5%)
Breakdown across open pole(int.)	.04	(4.0%)	.024	(3.6%)
Breakdown across open pole(ext.)	.01	(1.2%)	.010	(1.5%)
Locking in open or closed position	-	-	.190	(28.5%)
Others	.31	(31.0%)	.098	(14.6%)
No answer	(.59)		(.006)	-
	1.58	(100%)	. 67	(100%)

Table 7
mf-rate by characteristic for the second enquiry

Characteristic	Second enquiry mf per 100 cb-years	
Air or hydraulic oil leakage in operating mechanism	1.4	(30%)
Small SF6-gas leakage due to corrosion	0.7	(15%)
Small SF6-gas leakage due to other causes	1.1	(23%)
Change of functional characteristics	0.8	(17%)
Others	0.7	(15%)
No answers	0.0	(0%)
	4.7	(100%)

Table 8
Cause of the Major and minor failures for the first and second enquiry

Cause	Major Failures		minor failures	
	1st	2nd	1st	2nd
Design	} 45.3%	25.4%	} 52.5%	24.7%
Manufacture		28.7		39.1
Inadequate instructions	0.7	1.1	0.3	1.7
Incorrect erection	9.3	8.2	10.7	7.1
Incorrect operation	1.2	6.0	0.2	4.5
Incorrect maintenance	8.1	2.8	4.5	2.6
Stresses beyond specification	4.8	3.4	0.7	1.8
Other external causes	2.3	5.4	1.7	6.6
Other	28.3	19.0	29.4	11.9
	100	100	100	100

Table 9
Failure rates by type of operating mechanism
for MF and mf with origin "Mechanical failures in operating mechanism".

	Failure rates per 100 cb-years					
	< 200 kV		≥ 200 kV		all voltages	
	MF	mf	MF	mf	MF	mf
A Hydraulic mechanism, which may include spring	0.29	2.92	0.32	2.87	0.31	2.89
B Pneumatic mechanism, which may include spring	0.15	0.53	0.63	1.66	0.27	0.80
C Spring operated mechanism	0.20	0.22	1.21	2.75	0.27	0.40

Table 10

Estimated average interval between scheduled overhaul, estimated average labour effort and costs of spare parts for scheduled overhaul.

Table 10a: Estimated cost of scheduled servicing of High Voltage Circuit-Breakers above 63 kV from First International Enquiry for years 1974 - 1977.
(Includes ordinary servicing and detailed servicing for all technology circuit-breakers)

Interval between scheduled servicing (years)			Voltage class (kV)	Labour effort (manhours per cb-year)			Spare parts in manhours per cb-year					
Aver.	10%	50%		90%	Aver.	10%	50%	90%	Aver.	10%	50%	90%
2.3	1.0	3.0	5.0	63 ≤ V < 100	19.6	5	18	30	55.0	1	5	60
2.0	1.0	2.5	5.0	100 ≤ V < 200	34.0	10	30	72	38.2	3	12	60
2.0	1.0	3.0	6.0	200 ≤ V < 300	47.4	15	44	120	87.5	3	20	90
1.4	1.0	2.0	6.0	300 ≤ V < 500	48.5	14	50	169	72.7	10	38	158

Table 10b: Estimated cost for scheduled overhaul of High Voltage Circuit-breakers above 63 kV from Second International Enquiry for years 1988 - 1991.
(Includes scheduled overhaul for single pressure SF₆ gas circuit-breakers)

Interval between scheduled servicing (years)			Voltage class (kV)	Labour effort (manhours per cb-year)			Spare parts in manhours per cb-year					
Aver.	10%	50%		90%	Aver.	10%	50%	90%	Aver.	10%	50%	90%
7.6	4.0	6.0	12.0	63 ≤ V < 100	15.3	5	15	30	25.4	2	24	61
8.8	5.0	8.5	15.0	100 ≤ V < 200	17.4	3	12	43	20.7	2	8	48
8.2	4.0	7.9	12.0	200 ≤ V < 300	24.8	5	15	50	31.6	1	12	74
8.2	4.0	7.0	12.0	300 ≤ V < 500	31.0	5	18	56	17.7	2	8	48



3 - 5, rue de Metz
75010 Paris

1992 Session
30 August - 5 September

O

13-101

APPLICATION OF DIAGNOSTIC TECHNIQUES FOR HIGH VOLTAGE CIRCUIT-BREAKERS

by

A.L.J. JANSSEN* W. DEGEN M. TUDREJ S. IKEDA
Working Group 13.06**

On behalf of Study Committee 13

SUMMARY

Besides considering the reliability level of modern circuit breakers by means of a worldwide enquiry, WG 13.06 was also requested to study the impact of diagnostic techniques on reliability, maintenance, availability and life extension of high voltage circuit breakers. To fulfil this task a literature survey and evaluation was

made on diagnostic techniques. Furthermore, a questionnaire was circulated among the utilities and the manufacturers members of WG 13.06 getting to know about their practice and their opinion on the use of diagnostic techniques.

Additionally, the WG has established and published a certain number of definitions applicable to the literature evaluation and the questionnaire so that a sufficiently clear common language is available to deal with diagnostics.

As diagnostic techniques are used to improve the reliability and availability of the circuit breaker at the lowest overall costs, the following points of interest are considered:

- Objectives of the diagnostic techniques
- Most important parameters to be monitored
- Utilities practice of the diagnostic techniques
- Impact on the reliability and life cycle costs of circuit breakers
- Requirements on the reliability of the monitor itself

From the analysis of the results of the enquiries, it can be concluded that the diagnosis of some of the circuit breaker parameters has to be improved and that the diagnosis of other parameters can be reduced. In regard of the impact on the reliability and availability of circuit breakers and on the life cycle costs, a sensible use of diagnostic techniques is required.

KEYWORDS

Diagnostic Techniques, Reliability, Maintenance, High Voltage Circuit Breaker, Monitoring

** All the members of the Working Group 13.06 have contributed to this report by the information they have submitted and by their participation in the discussions.

Present membership of the Working Group:

J. Maaskola (Convenor) (FI), C.R. Heising (Secretary) (US), A. Bargigia (IT), E. Bruvik (NO), P.C. Botelho Neves (BR), N. Cuk (CN), J.C. Declercq (BE), W. Degen (DE), E. Dialynas (GR), P. Fletcher (GB), S. Ikeda (JP), M. Ishikawa (JP), A.L.J. Janssen (NL), J.L. Jaurique (ES), O. Karlen (SE), W. Lanz (CH), G.J. Meinders (US), R. Michaca (FR), V. Onu (RU), S. Peric (AU), J. Sikula (CS), S. Franc (YU), E. Thuries (FR), M. Tudrej (FR), V.N. Varivodov (SR).

The following past members of the Working Group also contributed to this work:

R. Baumgartner (CH), J. Beierer (DE), J. Brunke (US), L. Desmoulins (FR), I. Stahan (YU), D.F. Stevens (GB).

1. INTRODUCTION

CIGRE WG 13.06 ("Reliability of High Voltage Circuit Breakers") carried out world wide reliability studies on high voltage circuit breakers during the fifteen year period 1971 through 1985. An important part of the activities was to conduct the first international enquiry on circuit breaker failures and defects in service. These studies are reported in three CIGRE SC 13 final reports [1], [2], [3].

In 1986 a new CIGRE WG 13.06 was set up on "Reliability of High Voltage Circuit Breakers". The scope was to obtain detailed information of circuit breaker performance in service as well as possible measures to improve the reliability and to reduce the maintenance costs. Two major tasks were undertaken:

1. Conduct a second international enquiry on the reliability of high voltage circuit breakers in service.
2. Study the parameters for permanent supervision in service as well as relevant diagnostic methods.

The results of the second international enquiry on circuit breaker failures and defects in service should show the reliability improvement since the first enquiry.

The first enquiry was limited to circuit breakers placed in service after 1964 with a service voltage of 63 kV and above. The second enquiry was limited to single pressure SF6 circuit breakers, placed in service after 1 January 1978 with a rated voltage of 72,5 kV and above (including service voltages of 63 kV and above). The second enquiry covered the period 1 January 1988 up to 31 December 1991. An interim report with preliminary results (1988) of the second enquiry was presented at the 1990 CIGRE Session [4].

The studies on the application of monitoring and diagnostic techniques aim to contribute to the improvement of the reliability of operation and to the reduction of maintenance costs.

These studies will include all circuit breaker technologies. Metal-enclosed circuit breakers and circuit breakers in gas-insulated substations (GIS) are involved. Besides this, diagnostic techniques are even more of interest for other components of GIS [5].

The study on diagnostic techniques has been based on the following activities:

- consider appropriate definitions
- compile an overview of the commonly used techniques (supplied by the utility members of WG 13.06)
- compile an overview of new techniques from the utilities and literature
- get the utilities philosophy on the need of new diagnostic techniques
- draw conclusions from 1st and preliminary conclusions from 2nd enquiry.

A literature evaluation has been made on about 100 reports. 75% is dealing with diagnostic techniques for GIS-equipment. The outcome of the

analysis were 5 internal working documents with keywords, evaluation of the philosophy in the papers and techniques shown in the reports. WG 13.06 will publish a final report on the diagnostic techniques in 1993 with detailed information on these items.

2. DEFINITIONS

Most reports in the literature deal with sophisticated monitoring techniques. The studies of WG 13.06 deal with established techniques as well as new diagnostic techniques. They show how important it is to have a clear understanding of the relationships between such ideas as inspection, diagnostic tests, monitoring, supervision, continuous monitoring, on line-monitoring.

The definitions, used by WG 13.06 in the field of diagnostic techniques, are attached as appendix A.

Some definitions are taken from IEC 50, chapter 191 and from an internal IEC-document 17A (secretariat) 273. Other definitions are deduced from IEC 17 A (secretariat) 273 and IEC 50, chapter 351.

The relationship between these definitions are as follows:

- * Maintenance covers all actions: overhaul, diagnostic techniques and corresponding administrative actions.
- * Diagnostic techniques can be split up into inspection, diagnostic tests, and supervision.
- * Monitoring is a synonym for supervision.
- * If the sensors and dataprocessing devices are continuously connected to the circuit-breaker, it is called monitoring. Otherwise it is a diagnostic test technique.
- * If signals or data from the monitoring device are transmitted continuously, it is called continuous monitoring. Otherwise it is non-continuous or periodic monitoring.

3. OBJECTIVES AND PRACTICES OF DIAGNOSTIC TECHNIQUES

3.1. OBJECTIVES

The ultimate goal of maintenance, including actions like inspection, diagnostic testing and the application of monitoring techniques, is to establish or to improve the reliability and availability of the circuit-breaker. High reliability and availability have to be achieved at the lowest over all costs.

The maintenance philosophy and therefore the diagnostic techniques should be chosen on the basis of a real and necessary contribution to the reliability and availability of the circuit breaker.

Therefore the ultimate goal - improvement of the reliability and availability at the lowest cost - is translated into more concrete objectives. Each objective can be evaluated in terms of benefits that can be compared with the effectiveness and the cost of the particular diagnostic technique. The benefits are not restricted to the circuit breaker itself but can also incor-

porate other apparatus in the network or even the whole network.

The following objectives are applicable to both the nowadays commonly used diagnostic techniques and the more sophisticated techniques starting to come onto the scene:

- * monitoring of functional characteristics to either verify malfunctions or to detect abnormalities
- * prompt detection of changes in the functional characteristics in order to prevent a failure in the circuit breaker itself
- * location of failures, especially in GIS
- * prevention of unnecessary maintenance and dismantling, in order to prevent failures caused by improper maintenance [1], [2], [3]
- * reduction of life cycle costs
- * life extension of circuit breakers
- * evaluation of data of commissioning tests
- * input of accurate data for controlled switching

A possible future trend may be unattended substations, with a minimum of inspection. This tends towards strong requirements for a highly reliable monitoring system.

3.2. PRACTICES

3.2.1. Existing techniques

Based on the required reliability of the monitoring devices it makes sense to use them for circuit breakers if they are simple in application and interpretation, economical in initial costs and installation and reliable in operation. It was established by an enquiry among the members of WG 13.06 that it is more common to use the simple diagnostic techniques only.

An overview of the commonly used techniques is given in appendix B. The enquiry among the utility members was split up according to type of circuit breaker and type of operating system. The response of the enquiry was very similar for all participating utilities.

3.2.2. New techniques

Four of the utility members of WG 13.06 do not seriously consider to apply new diagnostic techniques, as the benefits are expected to be low. Another reason is the policy to exchange the old designs for new circuit breakers, rather than to apply new monitoring techniques to the old circuit breakers.

Four other utilities are planning to apply some new techniques and one utility expresses a need for new diagnostic techniques in order to place emphasis on the reliability and to overcome the difficulty with keeping an adequate maintenance staff. Besides this, the utility is expecting that the costs of sophisticated diagnostic techniques will be reduced, as the application becomes broader.

Six utility members did not express any companies philosophy on the application of new diagnostic techniques.

3.2.3. Relations with other systems

The developments in intelligent equipment is tremendous (control, protection, diagnostics) and with all that equipment, information of interest for the diagnosis of a circuit breaker can be made available. So the diagnostic techniques are not restricted to the equipment attached to or attachable to a circuit breaker. For example modern protection devices with their capabilities to monitor the control circuits from the protection relay up to the circuit breaker, to calculate and store the short circuit currents, to measure the time from the command to open up to the interruption of the current, to collect status-information of switchgear, etc. Similar information is gathered by substation control equipment. Also separate event recorders and disturbance recorders do supply valuable information to check the correct functioning of circuit breakers.

Two methods to relay information from the circuit breaker to the central office in an automatic way are possible: information collected via the control centre and information collected via a maintenance management system (dealing with maintenance reports, fault reports, coordination of overhaul, statistics).

4. ANALYSIS OF THE RESULTS OF THE ENQUIRIES

The parameters observed by a certain diagnostic technique can be subdivided into groups of subassemblies responsible for a failure and into groups of origins of a failure. From the literature evaluation and the failure card used in the second world-wide enquiry [4] the following groups are identified:

- operating mechanism
- tightness of SF6-gas system
- interrupting units
- electrical insulation
- electrical control and auxiliary circuits.

Some of the preliminary results of the second international enquiry are given in table I. This shows the absolute numbers of major failures (MF) and minor failures (mf) of the years 1988, 1989 and 1990. The final enquiry results will incorporate also 1991.

Table II compares the main categories of components responsible for the failures of the first and second enquiry.

The results of the first enquiry as described in [1], are translated to the main categories, used in the second enquiry. However one should keep in mind that the first international enquiry did cover all types of circuit breakers, while the second international enquiry is focused upon SF6-single pressure circuit breakers only.

The numbers are the failures per 1000 circuit-breaker-years. The percentages of the total number of MF or mf are also given in brackets.

TABLE I

PRELIMINARY RESULTS(1988-1990) FROM 2ND INTERNATIONAL ENQUIRY
OF HIGH VOLTAGE SF6 SINGLE PRESSURE CIRCUIT BREAKERS

(number of failures/defects per subassembly or component)

Component responsible for failures/defects	Number of Major Failures		Number of minor failures/defects	
1. Components at service voltage	67		590	
1.1. interrupting unit	41	(12.5%)	195	(8.5%)
1.2. aux. interr., resistor	3	(0.9%)	13	(0.6%)
1.3. main insul. to earth	23	(7.0%)	382	(16.6%)
2. El. control and auxiliary	109		525	
2.1. trip/close circuits	38	(11.6%)	28	(1.2%)
2.2. aux. switches	24	(7.3%)	49	(2.1%)
2.3. contactors, heaters, etc.	34	(10.4%)	149	(6.5%)
2.4. gas density monitor	13	(4.0%)	299	(13.0%)
3. Operating mechanism	138		1063	
3.1. compressors, pumps, etc.	50	(15.2%)	463	(20.1%)
3.2. energy storage	13	(4.0%)	162	(7.0%)
3.3. control elements	34	(10.4%)	293	(12.7%)
3.4. actuators, damping dev.	26	(7.9%)	111	(4.8%)
3.5. mech. transmission	15	(4.6%)	34	(1.5%)
4. Others	14	(4.3%)	122	(5.3%)
total	328	(100%)	2300	(100%)

TABLE II

RESULTS OF 1ST, AND PRELIMINARY OF 2ND INTERNATIONAL ENQUIRY

(failure rates per 1000 circuit-breaker-years)

Subassembly responsible for failures/defects	Major Failure rate		minor failure rate	
	1st	2nd	1st	2nd
1. Components at service voltg.	7.6 (48%)@	1.5(20%)	9.2 (26%)	13.0 (26%)
2. El. control and auxiliary	3.0 (19%)	2.4(33%)	5.7 (16%)	11.6 (23%)
3. Operating mechanism	5.2 (33%)	3.0(42%)	20.6 (58%)	23.5 (46%)
4. Others	-	0.3(4%)	-	2.7 (5%)
total failure rate	15.8 (100%)	7.2(100%)	35.5(100%)	50.8(100%)

@ including 20% for operating elements at service voltage, such as valves

Three quarters of the MF of the second enquiry are related to the operating mechanism and the electrical control and auxiliary circuits. The most important failure modes, in total 63,6% [6], are : "does not open or close on a command" and "locking".

It is worthwhile to compare the preliminary results of the second international enquiry (and the results of the first enquiry) with the groups of parameters described above.

4.1. Operating mechanism:

In the second enquiry the operating mechanism is blamed for the largest percentage of both the MF and the mf.

Most MF are of the failure modes "locking", "does not close or open on command". The most involved components are compressors, pumps, motors and the related pipework.

Most mf are of the origin "air or oil leakage". As 48% of MF in the first enquiry falling under HV-components incorporate also the HV-operating mechanism, 20% should be added to the 33% of MF mentioned under operating mechanism. In this way also in the first enquiry the operating mechanism has the highest number of MF. The same applies to the mf.

4.2. Tightness of SF6-gas system:

The first international enquiry did not consider the gas tightness.

The preliminary results of the second enquiry reveal also that about 9% of the MF and about 37% of the mf are reported under the origin tightness of SF6-gas system.

From table I it can be derived that the number of mf is rather high for a monitoring device. Although the number of MF due to the monitoring device seems to be low, it is unacceptable for just a monitor.

4.3. Interrupting units

Although the interrupting units are responsible for 12,5% of the MF and for 8,5% of the mf, the interrupting units show to be not critical according to just a few MF with the modes "does not make or break the current".

From the first international enquiry the coincidence in number of MF between these modes and the interrupting units is not known, but it appears to be a low number.

4.4. Electrical insulation:

Table III shows the failure rates for electrical breakdowns from both enquiries.

The number of breakdowns reported up to 1990 in the second national enquiry are incorporated in table III.

The electrical breakdown failure rate is 0,56 per 1000 circuit-breaker-years, compared with 1.31 in the first international enquiry.

4.5. Electrical control and auxiliary circuits:

The electrical control and auxiliary circuits are responsible for a third of the MF in the

second enquiry. Most of them belong to "does not open or close on command" and "locking".

In the first enquiry only 19% of the MF belonged to the category electrical control and auxiliary circuits; most of them also to "does not open or close on command".

It seems that the probability of a MF in these components, expressed per circuit breaker year, is the same for SF6 puffer breakers as for the old designs.

In the first international enquiry 16% of the mf and in the second enquiry a quarter of the mf belong to these components.

4.6. Conclusions:

From the above, it can be concluded that:

- the components of the operating mechanism, and especially the motors, compressors, pumps and pipes, are most important to consider for an improvement in the reliability and the application of diagnostic techniques.
- the same conclusion applies to the control and auxiliary circuits, especially as no improvement has been made with the modern SF6 puffers on this point, compared with the older technologies.
- the SF6 tightness and the reliability (including tightness) of the SF6 density monitor seem to need an improvement.
- failures to make and break the current occur infrequently and do not appear to warrant development and application of diagnostic techniques.
- as electrical breakdowns are serious failures, the development and application of diagnostic techniques in the field of electrical insulation are to be encouraged.

5. IMPACT ON RELIABILITY

5.1. IMPACT ON RELIABILITY

Distinction could be made between:

1. The improvement of the reliability of the circuit breaker, due to the use of the diagnostic techniques.
2. The reliability of the diagnostic technique itself.
 - 5.1.1. Improvement of the reliability of the circuit breaker

In regard to old breakers 3 possible ways to improve the reliability are practised by the utilities at present:

- install new circuit breakers of modern design
- give a major overhaul to the old breakers
- delay one of these actions by installing a monitor on breakers

At the moment it is not clear which action gives the greatest improvement of the reliability, although from the information in chapter 4, one may conclude that new circuit breakers of modern design are more reliable than old ones (a lower MF-rate) and that the items, which are the most valuable to monitor, many times are not covered entirely by existing techniques (operating mechanism, control and auxiliary circuits).

TABLE III

ELECTRICAL BREAKDOWN FAILURE RATES
RESULTS OF 1ST, AND PRELIMINARY RESULTS 2ND INTERNATIONAL ENQUIRY

(failure rates per 1000 circuit-breaker-years)

Breakdown modes	1st	2nd
Breakdown to earth	.41	.15
Breakdown between poles	.08	.04
Breakdown across an open pole (internal)	.63	.24
Breakdown across an open pole (external)	.19	.13
total electrical breakdown failure rate	1.31	.56
percentage of all Major Failures	8.3 %	7.8 %

TABLE IV

ESTIMATED COSTS FOR SCHEDULED OVERHAUL OF HIGH VOLTAGE CIRCUIT BREAKERS
(manhours per circuit-breaker-year)

FIRST ENQUIRY - all technologies 1974-1977

voltage range (kV)	labour effort				spare parts consumed			
	av.	10%	50%	90%	av.	10%	50%	90%
63<V≤100	20	5	18	30	55	1	5	60
100<V≤200	34	10	30	72	38	3	12	60
200<V≤300	47	15	44	120	88	3	20	90
300<V≤500	49	14	50	169	73	10	38	158

SECOND ENQUIRY - SF6 single pressure 1988-1990

voltage range (kV)	labour effort				spare parts consumed			
	av.	10%	50%	90%	av.	10%	50%	90%
63<V≤100	16	5	12	30	24	2	24	61
100<V≤200	18	3	12	44	23	2	9	48
200<V≤300	25	5	15	50	33	1	12	65
300<V≤500	28	6	18	56	17	2	9	48

TABLE V

ESTIMATED INTERVAL BETWEEN SCHEDULED OVERHAUL OF HV CIRCUIT BREAKERS
SECOND ENQUIRY - preliminary results of 1988-1990

voltage range (kV)	estimated interval (years)			
	av.	10%	50%	90%
63<V≤100	7.5	4.0	6.0	12.0
100<V≤200	8.6	5.0	8.0	12.0
200<V≤300	8.0	4.0	7.9	12.0
300<V≤500	7.8	4.0	6.5	12.0

In addition the monitoring technique itself may cause problems.

In regard to new breakers of new design the better way to improve the reliability of the circuit breaker is to test and improve its design and manufacture. The diagnostic technique has to be seen as an addition to the assessed quality of a circuit breaker. The value of a particular diagnostic technique can be evaluated with the objectives given before.

5.1.2. Reliability of the diagnostic technique

Especially with monitoring techniques it is important to achieve a reliability level that is higher than the reliability level of the circuit breaker, in order to get any benefits as discussed with the objectives.

In this regard it is important to realize that the duties and the environment of the monitoring equipment are completely different from equipment used in laboratories. For example all manufacturers do have test sets to measure the stroke and velocity of the operating rods during development and production tests, but that equipment is not guaranteed for the 2000 mechanical operation test of IEC publication 561

The reliability of the monitoring equipment has at least to be proven at the same tests as applied to the circuit breaker, for instance:

- dielectric tests
- mechanical and environmental tests
- short-circuit making and breaking tests
- capacitive current switching tests
- small inductive current switching tests

Special attention has to be given also, to the problem of electromagnetic interference. Besides specialised tests in this field, it is recommended to test the monitor together with the high voltage circuit breaker during all above mentioned duties.

The monitor has to be regarded as an integral part of the circuit breaker and has to function properly during those tests.

However, the short life cycle time of the electronic equipment, inclusive the necessary software, is less than the life cycle of the circuit breaker.

5.2. IMPACT ON MAINTENANCE

Table IV shows the estimated costs for scheduled overhaul for the first and the second enquiry. The costs are split up in labour effort and spare parts consumed. Both are expressed in manhours per circuit breaker per year. The 10, 50, and 90 percentiles are given along with the average cost value for each voltage category.

It can be seen that there is a wide variation between the 10 and 90 percentiles for the labour effort, typically as much as six to one or more. There is even a wider range for spare parts consumed. This holds true for the first enquiry with a variety of circuit-breaker technologies as well as for the second enquiry with modern single pressure SF6 circuit-breakers. These cost values indicate that many users of

high-voltage circuit-breakers may be doing more scheduled maintenance than needed. It might be possible to reduce the maintenance effort without the use of additional diagnostic techniques. In other cases it might be desirable to use additional techniques in order to detect degradation of the most probable failure modes before they occur in service.

The data given can be used to assist in estimating the maximum cost savings that might be possible from using appropriate diagnostic techniques on older or on newer technology circuit breakers.

Table V gives the interval between scheduled overhaul as estimated during the second enquiry. As with the costs, many utilities estimates may be based upon very limited or no experience with single pressure SF6 circuit breakers. The variation in the estimated interval is three to one, the average is 8 years for all voltage categories. Most manufacturers quote longer overhaul intervals than 8 years, but many utilities may not yet have sufficient confidence to fully exploit the longer overhaul interval possible with single pressure SF6 circuit-breakers.

6. CONCLUSIONS

- * Before the development of diagnostic techniques and/or the application of them manufacturers and users should consider the objectives they want to reach in terms of reliability, availability, maintenance and life cycle costs of both circuit-breaker and monitoring equipment.
- * Today's practice of all utilities of WG 13.06 shows that only well known diagnostic techniques have been used and that some see the need of applying completely new techniques.
- * The results of both enquiries show that some improvement in the reliability is still desirable. This can be achieved by the improvement of the reliability of the relevant components or in some cases by development of the existing diagnostic techniques.
- * In any case the application of diagnostic techniques may become in the future a natural consequence of the improvements in the field of electronics and information technology. The implementation of the same technology in protection, substation automation and supervisory equipment may offer the opportunity to incorporate monitoring functions for the circuit breaker.
- * It is expected that the sensible use of diagnostic techniques will lead to longer maintenance intervals and improvement of the reliability.
- * Common definitions should be used in the field of diagnostics as given in appendix A.

- [1] G. Mazza, R. Michaca
"The first International Enquiry on Circuit Breaker Failures and Defects in Service",
Electra nr. 79, December 1981, pp.21-91
- [2] J. Beierer, R. Kearsley, J. Verdon
"Maintenance of Modern High Voltage Circuit Breakers",
Electra nr. 102, October 1985, pp.119-131
- [3] R. Michaca, C.R. Heising, G. Koppl
"Summary of CIGRE Working Group 13.06 Studies on the Test and Control Methods intended to assure the Reliability of High Voltage Circuit Breakers".
Electra nr. 102, October 1985, pp.133-175
- [4] A. Bargigia, C.R. Heising, A.L.J. Janssen, J. Maaskola, R. Michaca
"Interim report on the second international enquiry on the reliability of high-voltage single pressure SF6 circuit breakers",
Paper No. 23-107 CIGRE session 1990.
- [5] J. Vigreux
"Application of condition monitoring techniques in gas insulated substations",
Electra nr. 134, February 1991, pp.47-59
- [6] A. Bargigia, W. Degen, C.R. Heising, M. Ishikawa, A.L.J. Janssen, J.E. Maaskola, R. Michaca, M. Tudrej
"High Voltage Circuit Breaker Reliability Data for use in System Reliability Studies - Interim Report CIGRE 13.06 Working Group",
Paper No 2-01, CIGRE symposium Montreal 1991

when the circuit breaker in service, to indicate the condition of the circuit breaker and/or to detect abnormalities and finally determine the optimum overhaul programme.

Inspection (IEC TC 17A (secretariat) 273):
Period examination of the principal features of the circuit breaker without any dismantling.
Note - This examination is carried out by inspectors and is generally directed toward the indication of pressure gauges and/or levels of fluids, tightness, position of relays, pollution of insulated parts, but actions such as lubrication, cleaning, washing, etc. which can be carried out with the circuit breaker in service, are included.

Diagnostic Tests (based on IEC TC 17A (secretariat) 273):

Comparative tests of the characteristic parameters of a circuit breaker to verify that it performs its functions, by measuring one or more of these parameters - carried out with sensors and dataprocessing devices, connected temporarily to the circuit breaker - and comparing the measured values with the specified values or previously measured values, from e.g. routine tests, commissioning tests.

Note - The tests are normally carried out, the circuit breaker being out of service.

Supervision, monitoring (50(191) IEC 191-07-26):
Activity, performed either manually or automatically, intended to observe the state of an item.
Note - Automatic supervision may be performed internally or externally to the item.

Supervision (of a circuit breaker),
Monitoring (of a circuit breaker) (based on IEC 50 (351)-01-05 and IEC TC 17A (secretariat) 273):

Automatic observation of the characteristic parameters of a circuit breaker to verify that it performs its functions, by measuring one or more of these parameters - carried out with sensors and data-processing devices, connected permanently to the circuit breaker - and automatically comparing the measured values with the specified values or previously measured values from e.g. routine tests, commissioning tests.

Note - Monitoring may be performed, the circuit breaker being in service or out of service.

Continuous monitoring (of a circuit breaker) (CIGRE 1990, 23-107): Monitoring in which the gathered data is transmitted continuously.

Non-continuous or periodic monitoring (of a circuit breaker) (CIGRE 1990, 23-107):
Monitoring in which the gathered data is transmitted non continuously or periodically.

Appendix A. DEFINITIONS

Maintenance (50(191) IEC 191-07-01):

The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function.

Overhaul (IEC TC 17A (secretariat) 273):

Work done with the objective of repairing or replacing parts which are found being below standard by inspection or test or as required by manufacturer's manual, in order to restore the component and/or the circuit breaker to an acceptable condition.

Diagnostic Techniques (CIGRE 1990, 23-107):

All kinds of inspection, measurement and/or monitoring, without actions of dismantling, even

Appendix B. COMMONLY USED DIAGNOSTIC TECHNIQUES

From a small enquiry among utilities from 8 countries an impression is given about the parameters checked by commonly used diagnostic techniques.

In the table the following symbols are used:

- . a single response
- * a couple responses
- ** most responses
- *** all or almost all responses

	inspection	diagn.test	monitor.
MAIN FUNCTIONS			
CB open or closed position			***
insulation quality	.	**	.
resistance of main circuit		***	.
temperature rise	**		
pole discrepancy		*	**
CB operating times		***	.
CB number of operations	***		.
accumulated breaking currents			.
INTERRUPTING OR INSULATING MEDIA			
pressure	*		*
density			***
SF6 quality		***	
compressed air quality	.	*	
fluid level	***		
fluid quality		**	
leakages	*	**	.
OPERATING MECHANISM			
pressure	.		***
stored energy		*	.
fluid level	***		*
leakages	***		
operating travel, speed		*	.
operating force		.	.
damping behaviour		.	.
pressure drop during operation		**	.
number of operations of motors	*		.
recharging times of motors		*	*
total running times of motors	*		.
CONTROL AND AUXILIARY EQUIPMENT			
auxiliary circuits energizing		*	**
coil supervision		*	*
closing lockout		*	**
auto reclosing lockout		.	**
general lockout		.	*
CB warning signal or alarm		*	*
heating circuits	**	*	
insulating quality		*	
MISCELLANEOUS			
corrosion	***		
pollution	***		
painting	*		



3-5 rue de Metz
75010 Paris

Symposium Berlin 1993

120-07

DIAGNOSTIC TECHNIQUES FOR HIGH VOLTAGE CIRCUIT-BREAKERS AND THEIR APPLICATION

by

A.L.J. JANSSEN* W. DEGEN M. TUDREJ S. IKEDA

Report on behalf of CIGRE Working Group 13.06 : Reliability of High Voltage Circuit-Breakers

SUMMARY

The final results of the second international enquiry are evaluated considering their impact on diagnostic techniques for high-voltage circuit-breakers and especially single pressure SF₆-gas circuit-breakers.

The parameters that are of importance for the application of diagnostic test techniques or monitoring techniques, are summarized. In a further chapter common and sophisticated diagnostic techniques to observe these parameters are discussed. To study the parameters, the techniques and their impact on the reliability of the circuit-breaker the report divides them into the following functions of the circuit-breaker:

- * make, carry and break current
- * electrical insulation
- * mechanical operation
- * control and auxiliary functions
- * tightness of SF₆-gas-system

According to the final results of the second international enquiry the first two functions do require no further development of diagnostic techniques. The operating mechanism is still the subassembly responsible for the most Major Failures and requires more attention to the quality control and diagnostic techniques. In order to improve circuit-breaker reliability, the last two functions either need a careful redesign of the subassemblies involved or improvement in diagnostic techniques.

For new diagnostic techniques the main objective should be to improve the reliability, availability, maintenance and life cycle costs of both the circuit-breaker and the monitoring equipment and not to develop sophisticated techniques.

KEYWORDS

Diagnostic Techniques, Reliability, Monitoring, High Voltage Circuit-breaker, Major Failure, minor failure

1. INTRODUCTION

CIGRE working Group 13.06 conducted 2 international enquiries on the reliability of high voltage circuit-breakers.

The first international enquiry, from 1974 through 1977, included 77892 circuit-breaker-years of all technologies at service voltages of 63 kV and above. The second international enquiry, from 1988 through 1991, covered single pressure SF₆-gas circuit-breakers with a rated voltage of 72.5 kV and above (including circuit-breakers applied at service voltages of 63 kV and above); in total 70708 circuit-breaker years.

To date WG 13.06 has published several reports on the preliminary results of the second international enquiry (see [1]). [1] deals with diagnostic techniques for high voltage circuit breakers.

This paper can be considered as an extension of [1]. In [1] the more general aspects of the diagnostic techniques such as definitions, objectives, impact on reliability and maintenance are discussed; while the present paper will pay attention to the more direct aspects such as the parameters to be observed by diagnostic techniques, the necessity and feasibility of certain techniques, future developments and the requirements for monitoring equipment.

In this paper, some relevant final results of the second international enquiry are presented. In 1994 WG 13.06 will publish a report with an overview of the final results, including information about the reliability, the accuracy and the confidence limits of the data.

2.SCOPE

The investigations of CIGRE WG 13.06 cover both air insulated high voltage circuit-breakers and circuit-breakers in gas insulated substations (GIS). In the second international enquiry a distinction has been made between metal-enclosed and non-metal-enclosed circuit-breakers. The first group includes dead-tank circuit-breakers in air insulated substations as well as circuit-breakers in GIS. The diagnostic techniques for metal-enclosed circuit-breakers are also partially applicable to the other compartments of a GIS. For these techniques, it is recommended to study the reports of SC 23, SC 15, SC 33 and especially of CIGRE WG 23.10 [2], [3], WG 15.03 [4] and WG 23/33.12 [5].

A number of diagnostic techniques, continuous monitoring techniques and diagnostic test techniques is applicable both to modern SF₆-gas circuit-breakers and to circuit-breakers of older designs.

Most continuous monitoring techniques, described in the literature, are dedicated to one particular type of circuit-breaker. From a technology, reliability and economical point of view, the continuous monitor must be delivered as an integral part of that circuit-breaker. Therefore this paper will dominantly pay attention to the application of monitoring techniques to new circuit-breakers of modern design. However, the diagnostic test techniques, referred to in this paper, will concern old and new circuit-breakers of any design.

3.FINAL DATA OF THE SECOND INTERNATIONAL ENQUIRY

Table I to VI give the most important results of the second international enquiry related to diagnostic techniques. Table I gives a comparison with the first international enquiry.

In the Tables and in the text the abbreviations MF and mf will be used for the Major Failures and minor failures; while ME and nonME will be used for metal-enclosed and non metal-enclosed. For the analysis of the MF-rates 475 failure cards have been used. For the analysis of the mf-rates 3358 failure cards have been used.

The results of the second international enquiry and, in the next chapter, the observable parameters will be treated according to the internal functions of a circuit-breaker i.e.:

- * make, carry and break the current
(interrupting units)
- * electrical insulation
- * mechanical operation (operating mechanism)
- * control and auxiliary function
(el. contr./aux. circ.)
- * tightness of SF₆-gas-system

If possible, the subassembly related to the internal function is given between brackets. The functions "electrical insulation" and "tightness of SF₆-gas-system" are covered by more than one sub-assembly. The "tightness of the SF₆-gas-system" is mentioned as a separate function as it does influence three other functions. The next paragraphs will refer to either the internal function or the subassembly.

3.1.INTERRUPTING UNITS

Although the interrupting units are responsible for 14.0 % of the MF and for 9.4% of the mf, the main function "to break" shows to be not critical as just a few MF correspond to the modes "does not make or break the current". See Tables II and III.

To put it the other way, the risk that a circuit breaker will not break a current is much higher due to the operating mechanism and the electric control and auxiliary circuits ("does not open on command") than due to the interrupting units ("does not break the current").

Obviously the development tests and quality tests in the field of power testing have reached a high level. Of course, it will be necessary to maintain this level by continuing the testing and certification programmes.

Most MF, for which the interrupting units are responsible, are electrical breakdowns and will be treated in the next paragraph.

3.2.ELECTRICAL INSULATION

Table VI shows the failure rates for electrical breakdowns for all circuit-breakers and separately for the ME and the nonME switchgear.

The overall electrical breakdown failure rate is 6.5 per 10000 circuit-breaker-years (compared with 13.1 in the first international enquiry). The electrical breakdown failure rate for metal-enclosed circuit-breakers is about the same: 6.3 per 10000 circuit-breaker-years and far less than the figures published for GIS-equipment on a bay-year-basis [5].

3.3.OPERATING MECHANISM

43% of the MF of the second international enquiry is related to the operating mechanism (Table I). The most important failure modes are: "does not open on a command", "does not close on a command" and "locking". (Table III) The operating mechanism causes the largest percentage of both the MF and the mf. The components most frequently involved are the compressors, pumps, motors and the related pipework. Most mf are of the characteristic "air or oil leakage". See Table V.

Furthermore, Table I shows a large decrease in the MF-rate caused by the operating mechanism (1st enquiry: 0.52 per 100 cb-years, 2nd enquiry: 0.29) and an equal mf-rate.

3.4.ELECTRICAL CONTROL AND AUXILIARY CIRCUITS

The electrical control and auxiliary circuits are responsible for 29% of the MF in the second international enquiry.

In the first international enquiry the MF-rate of the electrical control and auxiliary circuits was 0.30 per 100 circuit-breaker-years compared with 0.19 in the second enquiry; most of them are reported as "does not open or close on command".

In the first international enquiry the mf-rate was 0.57 per 100 circuit-breaker-years and in the second enquiry 0.92 (Table I).

From a reliability point of view, it is recommended to simplify the control and auxiliary circuits and to reduce the number of elements in the vital circuits. One should, for example, reconsider carefully the locking functions in the control circuits. It is highly desirable to improve the reliability of the control and auxiliary circuits.

3.5. TIGHTNESS OF SF6-GAS SYSTEM

The results of the second international enquiry reveal that 7% of the MF and 40% of the mf are reported under the origin "tightness of SF6-gas system". See Table IV.

From Table II, it can be derived that the rate of mf due to the gas density monitor is rather high for a monitoring device (10.7% of the mf and 4.0% of the MF). In the first enquiry, the gas density monitor was not separately identified because all technologies of circuit-breakers were included in the survey. The failures identified concerned valves and gauges, which are, in fact, equivalent components. The failure rate was half that reported in the second enquiry.

We must use these results with care because the definition of a failure due to tightness could be ambiguous, since not all participating utilities chose the same criteria to identify a failure due to SF6-gas-tightness. Some utilities consider a failure at each alarm or after each repair of a leak, or they summarize only one SF6-leakage per circuit-breaker per year to be reported in order to avoid too large a quantity of failure cards due to small SF6-gas-leakages.

An improvement is necessary in both gas tightness and the density monitoring system.

4. PARAMETERS FOR DIAGNOSTIC TECHNIQUES

The parameters that are to be considered for a diagnostic system, will be discussed by function or subassembly, as described in the last chapter. Both commonly used parameters and parameters for new development will be considered with respect to usefulness, experience and technical and economical feasibility.

In order to allow correct interpretation of the terms used for the diagnostic techniques Appendix A of [1] gives the definitions. In the publications of CIGRE WG 13.06 a distinction has been made between the diagnostic techniques used for inspection (gauges, counters), for diagnostic tests (infrared camera techniques, resistance measurements, timing tests) and for monitoring (those that generate a remote alarm or telemetered signal such as density monitor and locking alarm).

Appendix B of [1] presents an overview of the commonly used diagnostic techniques, as applied by the utility members of WG 13.06.

4.1. INTERRUPTING UNITS

4.1.1. ELECTRICAL ENDURANCE

According to the results of the second international enquiry for modern SF6 circuit-breakers the electrical endurance doesn't seem to be critical in spite of its functional importance. The experience of the members of WG 13.06 is in

line with this conclusion.

Several papers describe tests and experience with a large number of interruptions of (short circuit) current [6], [7], [8]. Besides the number of interruptions and the magnitude of the interrupted current, it is also important to know the arcing times. Although the arcing times are not well described in all papers the general feeling is nevertheless that only the interruption of short circuit current of large amplitude has a substantial influence on the electrical endurance of the arcing contacts and nozzles.

Because of this, it is not considered necessary to summate small interrupted currents for SF6-gas circuit-breakers and the need to automatically summate large short circuit currents is questionable since the number of such interruptions will probably be low and can be dealt with in other ways (for example within a maintenance management system).

For circuit-breakers of older designs (such as bulk oil and minimum oil) the summation of currents is a more important parameter since the number of interrupted short circuit current that triggers a major overhaul is limited compared with the modern single pressure SF6-gas circuit-breakers.

Many different ways to monitor the interrupted current are described in the literature such as counting all currents, counting only the short circuit current or taking the sum of the square of the current during a certain time interval (representing the arcing time) [9]. A direct measurement of the arcing time for the purpose of summation of interrupted current times arcing time is not known. One paper describes a method to measure optically the non-appearance of certain metal ions in the arc, in this way checking that the arcing contacts have not been worn out [10].

Apart from these continuous monitoring techniques, the literature also gives examples of diagnostic test techniques. For example, while operating the circuit-breaker with a low velocity, the measurement of the increment in the friction forces, caused by the rougher arcing contacts [11] and dynamic contact resistance measurement techniques [6], [7], [12]. Several authors propose to use SF6-gas analysis, measurement of the pd-level or measurement of an increase in vibrations of the structure, caused by rubbing of the rougher arcing contacts, as tools to evaluate the status of the arcing contacts. All these techniques are still experimental and far from common engineering practice.

4.1.2. ELECTRICAL CONTACT

The electrical resistance of the main contacts and the main connections between current carrying parts forms an important parameter, although the number of MF "fails to carry the current" due to the interrupting units is very small (see Table III).

The most commonly used technique to test the electrical contacts is the measurement of the resistance of the main contacts with the circuit-breaker in a closed position (diagnostic test). In addition many users utilize the infrared camera technique to look for bad electrical

contacts.

The literature refers to the infrared technique, SF₆-gas analysis and measurement of acoustic vibrations in the enclosure of metal-enclosed switchgear as possible methods to detect bad electrical contacts. Several authors mention the application of temperature sensors to metal-enclosed circuit-breakers.

A significant breakthrough in these experimental techniques is not expected. However, an improvement in the commonly used diagnostic test techniques (for example by putting the results in a databank for direct comparison with historical measurements and the calculation of trend-curves [13] will probably find a broad application.

4.1.3. OTHER PARAMETERS

Some authors are looking for other parameters that influence the interrupting capabilities of a circuit-breaker. The dynamic pressure of the SF₆-gas in the arcing chamber and the light emission of the arc are examples for this [10]. The diagnostic techniques suggested are more suitable for development tests and not for monitoring purposes in service.

4.2. ELECTRICAL INSULATION

4.2.1 QUALITY TESTS

The commonly used diagnostic techniques for the quality of the electrical insulation are diagnostic tests such as moisture content of the oil, air or SF₆-gas; dielectric breakdown voltage of the oil; dielectric loss tangent of the bushings or pd-level for metal enclosed circuit-breakers. The last one will be treated in a separate paragraph.

For SF₆-gas circuit-breakers the general feeling is that, in principle, the quality of the gas is adequate. However, the quality could be reduced due to leakages with consequent entrance of humidity or due to opening the circuit-breaker using incorrect procedures again with humidity problems. Testing of the humidity content of the SF₆ gas after opening or severe leakage is strongly recommended.

4.2.2 QUANTITY TESTS

The quantity of oil is checked during the periodic inspections of the circuit-breaker (oil level and oil leakages). The quantity of SF₆-gas is monitored with the density-monitor (see in paragraph 4.5)

4.2.3. PARTIAL DISCHARGES

Although the number of electrical failures in metal enclosed circuit-breakers is low, the impact of such a failure, when the circuit-breaker is integrated in a GIS is large. Many papers, among which is a report of CIGRE WG 23.10 [3], show a growing interest in the development of adequate monitoring and diagnostic test techniques in this field.

Partial discharges (p.d.) in GIS are caused by imperfections in the spacers such as voids; by electrically loose metal parts, such as screens; by metal particles or by protrusions on the conductors. In a direct or indirect way p.d. can result in flashovers.

In the literature many papers give methods to

detect p.d.'s. These techniques are related to the acoustic emission, SF₆-decomposition, light emission, potential rises, electrical field pulses and electromagnetic emission. Some authors apply a combination of diagnostic techniques.

Most of the techniques described are monitoring techniques. The technical and commercial feasibility of the monitoring techniques suggested has not yet been demonstrated [14]. However, the techniques, that can be used as diagnostic test techniques are applicable to more than one GIS and seem to be commercially available. In [14] and [16] an overview of the state of the art can be found.

Another field of interest for pd-detection techniques is their use during on-site commissioning tests of GIS. Many papers and reports refer to the application of diagnostic test and monitoring techniques during on-site dielectric tests. The number of flashovers during on-site dielectric tests is relatively high and not representative of the insulation quality in service (far less electric breakdown failures are reported) [5]. For some defects, the discriminating effect of a power frequency voltage test with a value a little higher than the rated value, plus the application of a pd-detection technique, is believed to be better than an AC-voltage test with higher values.

Many working groups within CIGRE, IEEE and other bodies are studying this field of application of diagnostic techniques [3], [4], [5], [14].

Detection of pd's is one, to locate the pd and to extract reliable and accurate information from the measurement is another problem. Pd-test and -monitoring systems have to be designed and tested for these application requirements.

The need for a technique to locate a pd rather than an electrical breakdown depends on the number of dielectric failures. The low electrical failure rate of metal enclosed circuit-breakers in service does not support the necessity for complicated pd-detection and location techniques. It may be that the dielectric failure rate in other compartments leads to a need for reliable, accurate and economically feasible pd-location techniques [3].

4.2.4. FAILURE LOCATION OF ELECTRICAL BREAKDOWNS

A way to locate an electrical breakdown failure in a GIS is to analyze the signals from the protection relays, the event printers and the perturbation recorders. Furthermore, SF₆-gas-analysis and special pressure switches or density-monitors can give valuable information. Some users have implemented optical sensors to detect the occurrence of a flashover and to locate it.

In the literature sophisticated pd-techniques, optical techniques, temperature rise detection techniques, acoustic vibration techniques, magnetic techniques and ground current detection techniques are mentioned as possible electrical failure location techniques.

Whatever technique is used, the GIS should be monitored continuously, since information on the relevant parameters must be collected at the moment the failure occurs.

4.3. OPERATING MECHANISM

4.3.1. NUMBER OF OPERATIONS

A very important parameter for the status evaluation of the operating mechanism is the number of operations. All surveyed utilities and manufacturers implement counters for the number of mechanical operations, the checking of which has to be put on the inspection list.

4.3.2. OPERATING TIMES

Another important parameter is the operating time. For all utilities, checking the operating time is the most significant diagnostic test. Some utilities also measure the velocity of the pull rods and, as shown in Appendix B of [1], one utility is measuring the force in these rods. Also the damping behaviour is sometimes checked.

In the field of diagnostic techniques utilities are looking for equipment to support the diagnostic test described in order to reduce the time needed to test a circuit-breaker, get direct results from the measurements, get the possibility to compare the results with historical, statistical or reference data, to get more information (all arcing chambers and poles at one time together with auxiliary contacts; travel and velocity; complete OCO-cycle) or get the possibility to measure a circuit-breaker in service. This last test could also be interesting when there is some doubt about the first operation after a long period without mechanical operations.

For some of these diagnostic tests, commercial testsets are available. For other functions the testsets are still experimental or under development.

A further evolution is continuous monitoring of the operating time or travel and velocity. Several authors and also a number of utilities are developing different monitoring techniques depending on the necessary accuracy of the time measurement. This can be a timer connected to the auxiliary contacts (one has to be careful with the mechanical scattering of the auxiliary contacts and of auxiliary relays) or more specialised equipment such as optical sensors, bar code techniques, special auxiliary contacts or potentiometers.

One author uses optical fibres in the arcing chamber to monitor amongst other parameters, the arcing time [10].

However, no information is available yet on the accuracy required of the continuous timing monitor in order to provide useful data from which the maintenance staff can draw conclusions. Possibly one also has to measure the auxiliary voltage level or the environmental conditions such as temperature and humidity. A thorough investigation in this field will be required, before a wide implementation of these monitoring techniques can be expected.

4.3.3. LEVELS AND PRESSURES

A third group of interesting parameters of the operating mechanism are fluid- and pressure levels of hydraulic oil, nitrogen and air. Most utilities monitor the pressure levels but check the oil levels and leakages by inspections. Several utilities check the stored energy and the pressure drop in the operating mechanism during diagnostic tests.

The literature describes monitoring systems that supervise the dynamic behaviour of the fluids and gases in the operating mechanism and also in the arcing chamber.

At the moment less information is available on the variations of the dynamic parameters and especially on the dynamic characteristics. As such it is not possible yet to detect or predict failures and defects. An investigation in more depth is necessary on the behaviour of the dynamic parameters.

4.3.4. PUMPS AND COMPRESSORS

The fourth group of parameters is the number of operations of pumps and compressors (motors), the recharging times and the total running times. The utilities may look after these parameters by inspection (counters, clocks), diagnostic tests (stop-watching the recharging time) or monitoring (time-relay).

Some authors develop monitors that use these parameters, sometimes extended with motor-current and current through the opening and closing coils.

Considering the results of the second international enquiry on the item compressors, pumps, etc., more attention should be paid to the application and simplification of monitoring techniques in this field.

A common way to check the correct operation of the circuit-breaker and the related control wiring is to operate it about once a year.

4.3.5. OTHER PARAMETERS

Several papers describe new diagnostic test techniques such as systems that record and evaluate the acoustic vibrations in the structure of a circuit-breaker during normal or slow speed operations. The experience with these techniques, when referring to the possibility to detect and predict failures, is still very limited.

4.4. ELECTRIC CONTROL AND AUXILIARY SYSTEM

4.4.1. ELECTRICAL CONTROL SYSTEM

Taking into consideration that an important part of all MF can be related to failure modes such as "does not close or open on command" it can be concluded that it would be desirable to pay more attention to the supervision of these vital functions.

Most utilities monitor a number of parameters in the electrical control system such as coil supervision, energisation of auxiliary circuits and the lockouts of the circuit-breaker. In general, even more monitoring activities are incorporated in modern SF6-gas circuit-breakers than the older designs. Monitoring functions are also quite often fulfilled by protection equipment (monitoring the coils and wiring) or control systems (monitoring auxiliary contacts and energisation of the auxiliary circuits).

Some authors foresee a future control system with micro-processor logic schemes. From a reliability point of view a completely different development is desirable which could be the choice to simplify the control circuits as much as possible and to reconsider carefully the locking functions and automatic switching (pole-discrepancy).

4.4.2. ELECTRIC AUXILIARY SYSTEM

Many utilities make use of a single alarm per circuit-breaker or group of circuit-breakers when telecontrolling the circuit-breaker (the tele-alarm). Detailed information about the alarm is available in the substation or in the circuit-breaker cabinet. In these circumstances the benefit of implementing sophisticated monitoring equipment should be evaluated.

In the commonly used monitoring techniques one uses the status of a microswitch which signals the passing of a threshold such as a pressure switch in the operating mechanism, a temperature compensated pressure switch in the density monitor or a time relay to supervise the charging time of a motor.

In the literature, the use of a microprocessor based monitor is often described to calculate the important figures, evaluate the results, compare them with historical data and transmit an alarm when necessary. The more sophisticated techniques make use of sensors that give a measured value such as the pressure or pressure drop in a hydraulic system, the temperature and pressure of the SF₆-gas or the running time of a motor. Many authors suggest the use of optical sensors and optical fibres for the measuring functions.

The new monitoring techniques are focusing on trends in the variations of the measured signals rather than on passing a certain threshold. Sometimes the monitor is dealing with dynamic values rather than static values.

Almost all microprocessor based monitoring systems use complicated mathematical techniques to extract the main features out of erratic signals or to compare the result of a calculation with historical data.

On one hand a microprocessor based monitor offers many possibilities to collect, to present, to store and to transmit information including information about the monitor itself, especially when the monitoring system will be part of an overall computerized substation control concept. A microprocessor based control and auxiliary system can be better organised and is more flexible for customisation.

On the other hand the microprocessor and its related hardware, the previously complicated sensing techniques and the software modules have to be highly reliable and in addition be implemented in an apparatus that has to withstand tough environmental and functional conditions.

For the present, most utilities would be satisfied with a much simpler monitor that handles static values and that signals the passing of a certain threshold by well-established techniques.

4.5. TIGHTNESS OF SF₆-GAS SYSTEM

The second international enquiry reveals that many failures (minor, but also Major) occur because of SF₆-gas-tightness including the density monitor. The commonly used density-monitor is a single, temperature compensated (be it by bimetal or by reference volume), pressure switch that is connected to the three poles.

Most techniques proposed in the literature measure the pressure of the SF₆-gas and the temperature of the gas or the enclosure. One author does not use the temperature for inside applications [15].

In two papers the moisture or air content of the SF₆-gas is recommended as a parameter for monitoring tightness.

However, the objective of the proposed new techniques is seldom to improve the gas-tightness of the system. Nevertheless the industry has to be encouraged to improve the tightness of the whole gas-system including the monitor.

5. FUTURE SYSTEMS

Two stages of development of monitoring equipment can be distinguished. In the literature, it is often referred to a monitor which fulfils one or more supervising functions and sends an alarm to the control centre when necessary, all important information is available at the monitor adjacent to the circuit breaker.

This level of monitoring equipment requires communication links between the monitor and the substation building. Also, communication between the monitor and the circuit breaker has to be considered. A monitor with reliable and more economic communication methods than the commonly used systems will have a change of acceptance in the future, others will not [9].

The second stage of development is to integrate monitoring functions into a co-ordinate system which fulfils many other requirements such as control, interlocking, system protection and communications. These computer-based systems are connected to a local area network allowing transfer of information between substation bays and the control centre. Information is gathered and transmitted in digital form.

Since the load imposed on current and voltage sensors by these systems is low, the introduction of alternative techniques for measurement of current and voltage will be feasible. Such techniques could be incorporated in the circuit-breaker.

A communication system as just described, needs a high level of standardization of information and protocols. The introduction of such techniques will be driven by control and protection experts. A close cooperation between these experts and the circuit-breaker experts will be necessary in order to develop a continuous monitoring system that will be economically feasible since it will also fulfils other functions.

The required reliability of the sensors and the other diagnostic equipment connected to the circuit-breaker has to be proven by a thorough testing together with type testing of the circuit-breaker, as stated in [1]. Special attention has also to be given to the problems of electromagnetic interference.

Finally, the statement can be put forward that, before and during the development of new diagnostic techniques, one has to consider carefully the objectives one wants to achieve with the monitoring or diagnostic test equipment. See

also [1].

6. CONCLUSIONS

The second international enquiry on the reliability of single pressure SF₆-gas-circuit-breakers with a rated voltage of 72.5 kV and above (or applied at system voltages of 63 kV and above) covers 70708 circuit-breaker-years.

6.1. MAIN RESULTS

* The final results show a large improvement of the Major Failure rate compared with the reliability of circuit-breakers of all designs as studied in the first international enquiry.

* The minor failure rate of single pressure SF₆-gas circuit-breakers has shown an increase compared with the first international enquiry.

* The failure rates related to electric endurance and dielectric breakdown have proved to be very low. This applies to both ME and non-ME circuit-breakers.

* As with the first international enquiry, the operating mechanism and electric control and auxiliary circuits are the subassemblies responsible for most MF as well as mf.

* The MF and mf rates related to SF₆-gas-tightness including the density monitor are substantial.

6.2. NECESSARY IMPROVEMENTS

From the results above, the following statements can be deduced:

* The most important parameter to monitor is the density of the SF₆-gas. A further improvement is necessary with respect to the SF₆-gas-tightness of the circuit-breaker.

* Other important parameters for diagnostic techniques are those of the operating mechanism.

* It is recommended to improve the reliability of electrical control and auxiliary circuits.

6.3. REQUIREMENTS FOR IMPROVED AND NEW DIAGNOSTIC TECHNIQUES

The improvements necessary could be achieved either by redesign of the less reliable components or existing diagnostic techniques or by the application of new diagnostic tools. In any case, before the development of diagnostic techniques and/or their application, manufacturers and users should consider the objectives they want to achieve in terms of reliability, availability, maintenance and life cycle costs of both circuit-breaker and monitoring equipment.

* Advanced monitoring techniques need more effort to be devoted to the study of the behaviour of the observed parameters of the circuit-breaker.

* Future developments could possibly lead to an integration of circuit-breaker monitoring functions with control and communication functions. Close cooperation of circuit-breaker specialists with the experts involved in the

fields of protection and substation control is recommended.

7. LITERATURE

- [1] A.L.J.Janssen, W.Degen, M.Tudrej, S.Ikeda
"Application of Diagnostic Techniques for High Voltage Circuit-Breakers",
CIGRE Session 1992, Report 13-101
- [2] J.Vigreux
"Application of Condition Monitoring Techniques in Gas Insulated Substations",
Electra nr. 134, February 1991, pp. 47-59
- [3] T.Molony
"A Twenty-five-year Review of Experience with SF₆ Gas Insulated Substations (GIS)",
CIGRE Session 1992, Report 23-101
- [4] CIGRE WG 15.03
"Diagnostic Methods for GIS Insulating Systems",
CIGRE Session 1992, Report 15/23-01
- [5] CIGRE WG 33/23.12
"Insulation Co-ordination of GIS: Questions on the Influence of On-Site Tests and Dielectric Diagnostics",
CIGRE Session 1992, Report 23/33-03
- [6] A.Stokes
"Circuit-Breaker diagnostics",
CIGRE Session 1988, Report 13-03
- [7] M.Runde, T.Aurud
"Non-Invasive Condition Evaluation of Circuit-Breakers",
CIGRE Session 1992, Report 13-106
- [8] A.Pons, A.Sabot, G.Babusci
"Electrical Endurance and Reliability of Circuit-Breakers. Common Practice of Two Utilities",
IEEE 1992 WM, Report 242-8 PWRD
- [9] R.Jeanjean, M.Landry, A.Chenier, D.Demissy
"Electronic System for Controlling and Monitoring the Mechanical and Electrical Integrity of HV Circuit-Breakers",
CIGRE Session 1988, Report 13-11
- [10] G.R.Jones, S.M.G.Ali, T.Irwin, D.Parr
"Circuit-Breaker Monitoring using Optical Fibre based Systems",
CIGRE Session 1988, Report 13-09
- [11] S.Ikeda, A.Aoyagi, T.Amamiya
"Diagnostic Technique for Mechanical Failures of Gas Circuit Breakers",
IEEE Vol.PAS-100, No.12, December 1981, pp. 4869-4875
- [12] P.Hoff, A.Holm, O.Carlen, U.Lager, U.Akesson
"Condition Monitoring of SF₆ Circuit-Breakers",
CIGRE Session 1992, Report 13-104
- [13] F.Nakajima, E.Kawagoe, M.Horikoshi, K.Sasaki
"Methods and future Trend to improve Reliability of Circuit Breakers",
CIGRE Session 1992, (Report 13-107)
- [14] IEEE Substations Committee, WG K4
"Partial Discharge Testing of Gas Insulated Substations",
IEEE/PD, Vol.7, No.2, pp. 499-506
- [15] L.Lundin
"Condition Monitoring of Medium-Voltage Circuit-Breakers",
CIGRE 1985, Conference Publ.250, pp. 49-52
- [16] A.Bargigia, W.Koltunowicz, A.Pigini
"Detection of Partial Discharges in Gas insulated Substations"
IEEE/PD, Vol.7, No.3, pp.1239-1249

TABLE I
COMPARISON OF THE FINAL DATA OBTAINED FROM THE 1ST AND 2ND INTERNATIONAL ENQUIRY ON THE RELIABILITY OF HIGH VOLTAGE CIRCUIT-BREAKERS IN SERVICE (failure rates per 100 circuit-breaker-years)

Subassembly responsible	Major failure rate		minor failure rate	
	1st	2nd	1st	2nd
1. Components at service voltage	.76 (483)	.14 (213)	.92 (763)	1.44 (312)
2. EL, control and aux. circuits	.30 (192)	.19 (292)	.57 (162)	.92 (202)
3. Operating mechanism	.52 (332)	.29 (432)	2.06 (582)	2.05 (442)
4. Others		.05 (72)		.25 (52)
Total failure rate	1.58 (1002)	.67 (1002)	3.55 (1002)	4.66(1002)

@ Including 20 I for operating elements at service voltage, such as valves

Number of cb-years of 1st international enquiry: 77892; all technologies applied at a service voltage of 63 kV and above. Number of cb-years in 2nd international enquiry: 70708; single pressure SF6-gas cb's at a service voltage of 63 kV and above.

TABLE II
SUMMARY OF FINAL DATA FROM 2ND INTERNATIONAL ENQUIRY ON THE RELIABILITY OF HIGH VOLTAGE SF6 SINGLE PRESSURE CIRCUIT-BREAKERS (number of failures/defects per subassembly or component)

Component responsible for failures/defects	Number of Major failures	Number of minor failures/defects
1. Components at service voltage	99	1019
1.1. interrupting unit	66 (14.02)	310 (9.42)
1.2. aux. interc. resistor	6 (1.32)	20 (0.42)
1.3. main insul. to earth	27 (5.72)	689 (20.72)
2. EL, control and auxiliary circuits	137	650
2.1. trip/close circuits	47 (10.02)	49 (1.52)
2.2. aux. switches	35 (7.42)	69 (2.12)
2.3. contactors, heaters, etc.	36 (7.62)	178 (5.42)
2.4. gas density monitor	19 (4.02)	354 (10.72)
3. Operating mechanism	204	1449
3.1. compressors, pumps, ecc.	64 (12.62)	615 (18.72)
3.2. energy storage	36 (7.62)	238 (7.22)
3.3. control elements	44 (9.32)	383 (11.62)
3.4. actuators, damping dev.	42 (8.92)	168 (5.12)
3.5. mech. transmission	18 (3.82)	45 (1.42)
4. Others	32	178 (5.42)
Total	472 (1002)	3296 (1002)
subassembly responsible not indicated on failure card	3	62

TABLE III
CORRELATION CONCERNING THE CHARACTERISTICS OF THE MAJOR FAILURE AND THE SUB-ASSEMBLY RESPONSIBLE

Sub-assembly responsible (not indicated: 4)	Does not open or close on command incl. locking opens or close without command	Does not break, make or carry the current	Electr. breakdown	Others
Component at serv.voltg.	25	19	39	14
Electrical control and aux. circuits	126	5	0	5
Operating mechanism	167	4	2	30
Others	8	1	3	18
Numbers of events	376	29	46	67

TABLE IV
ORIGIN OF THE MAJOR AND MINOR FAILURES FOR ALL VOLTAGES

Number of events	HF	MF
Mechanical in operating mechanism	475	3358
Mechanical in other parts of cb	203	1275 (392)
Electrical (main circuit)	48	319 (102)
Electrical (control and aux.)	64	29 (12)
Tightness of SF6-gas system	113	330 (102)
	33	1280 (402)
Total	461 (1002)	3233 (1002)
Origin not indicated on fail. card	14	125

TABLE V
CHARACTERISTICS OF THE MINOR FAILURES FOR ALL VOLTAGES

Number of events	HF	MF
Air or leakage in operating mechanism	3358	999 (302)
Small SF6 leakage due to corrosion		528 (162)
Small SF6 leakage due to other causes		769 (232)
Change in functional characteristics		543 (162)
Others		493 (152)
Total	3358	3332 (1002)
Characteristic not indicated on failure card	26	

TABLE VI
ELECTRICAL BREAKDOWN FAILURES FOR ALL VOLTAGES

Number of cb-years	HF	nonHF
ALL	70708	40308
Breakdown to earth	15	5
Breakdown between poles	7	2
Breakdown across open pole (internal)	17	16
Breakdown across open pole (external)	7	4
Total	46	27
Per 10000 cb-years	6.5	6.7

13-201

**FINAL REPORT ON HIGH-VOLTAGE CIRCUIT BREAKER RELIABILITY
DATA FOR USE IN SUBSTATION AND SYSTEM STUDIES**

by

C.R. HEISING* E. COLOMBO A.L.J. JANSSEN J.E. MAASKOLA E. DIALYNAS

Paper on behalf of Working Group 13.06

ABSTRACT: CIGRE 13.06 Working Group has conducted two international enquiries on the reliability of high voltage circuit breakers 63 kV and above. The first enquiry included 20,000 breakers of all technologies and covered the years 1974 thru 1977. The second enquiry included 18,000 single pressure SF6 breakers for the years 1988 thru 1991. A special effort has been made to collect data that can be used in substation and system reliability studies. These data include both the circuit breaker major failure rate and the circuit breaker downtime at each of several different voltages. Probabilities have been calculated for various breaker failure modes: such as, "does not open on command," "does not break the current," "does not close on command," and "does not make the current." The results from these two enquiries are presented and compared.

A brief description is given of the scope and objectives of the CIGRE 13.06 Working Group on the Reliability of High Voltage Circuit Breakers. The objectives include collecting circuit breaker reliability data that is much more detailed than required for substation or system reliability studies. The additional detail is used for improving the reliability of circuit breakers.

1. INTRODUCTION

CIGRE 13.06 Working Group carried out world wide

KEY WORDS: Circuit Breaker, Reliability Definitions, Reliability Data, Failure Modes, System Reliability

* All the members of the WG 13.06 have contributed to this report by the information they have submitted and their participation in the discussions. Other present members are: H. Bruvik (NO), N. Cuk (CA), J. Declerq (BE), W. Degen (DE), P. Fletcher (GB), W. Franca (BR), O. Karlen (SE), W. Lanz (CH), G. J. Meinders (US), V. Onu (RU), S. Peric (AU), G. Sanchis (FR), J. Sikula (CZ), E. Thurie (FR), M. Tudrej (FR), M. Tsuchiya (JP), V. N. Varivodov (CIS), E. Zaima (JP). The following past members and guests also contributed to this work: A. Bargigia (IT), R. Baumgartner (CH), J. Beierer (DE), P. C. Botelho Neves (BR), J. H. Brunke (US), L. Desmoulins (FR), S. Ikeda (JP), M. Ishikawa (JP), R. Jeanjean (FR), R. Michaca (FR), I. Stahan (YU), D. F. Stevens (GB).

reliability studies on high voltage circuit breakers during the fifteen year period 1971 through 1985. This included making the First International Enquiry on circuit breaker failures and defects in service. Studies were also made on new testing and maintenance methods for improving the reliability of high voltage circuit breakers. This work is reported in three CIGRE Study Committee No. 13 final reports [1][2][3]. Some of the CIGRE 13.06 WG recommendations have resulted in changes in International Standards for high voltage circuit breakers.

2. SCOPE AND OBJECTIVES OF NEW CIGRE 13.06 WG

In 1986 a new CIGRE 13.06 Working Group was set up on "Reliability of High Voltage Circuit Breakers" in order to obtain detailed information on circuit breaker performance in service as well as possible measures to improve the reliability and to reduce the maintenance costs. Two major tasks were undertaken:

1. Conduct a Second International Enquiry on the in service reliability of SF6 single pressure high-voltage circuit breakers with rated voltages 72.5 kV and above.

2. Study the parameters for permanent supervision in service as well as relevant diagnostic methods.

The results of the Second International Enquiry on circuit breaker failures and defects in service show the change in reliability since the First Enquiry. Monitoring and diagnostic methods aim to improve the reliability of operation and contribute to reducing the cost of maintenance. Studies on monitoring and diagnostic methods include all circuit breaker technologies because there is interest for both new and older circuit breakers.

An interim report of the CIGRE 13.06 WG was given at the 1990 CIGRE Session [4]. Preliminary results of the reliability data for use in substation and system reliability studies were presented in a 1991 paper [5]; and the final results are contained in this paper. Two other papers on the final results of the Second International Enquiry have been published in 1993 and 1994 [6][7]. Ref 7 is an overview of several planned final papers that each analyse the results from a different point of view.

* 216 Farwood Road - WYNNEWOOD, PA 19096 - United States

3. RELIABILITY DEFINITIONS USED IN TWO INTERNATIONAL ENQUIRIES

The CIGRE 13.06 WG wrote circuit breaker reliability definitions in 1971 for "failure," "major failure," "minor failure," and "defect." These definitions were used in both the First and Second International Enquiries and are given in Table 1. Thus world wide reliability definitions have existed for several years for high voltage circuit breakers and are now included in technical report IEC 1208 (1992) "Guide for High-Voltage Alternating Current Circuit Breaker Maintenance" by TC17 on Switchgear and Controlgear. It can be seen that the term "circuit breaker major failure" is equivalent to what system planning people would call a "forced outage."

The term "circuit breaker downtime" was clearly defined in the Second International Enquiry as "time from discovery of the failure until the breaker is returned to service, exclude deliberate delays." In the First International Enquiry "circuit breaker downtime" was calculated by adding two terms: (1) "time required to analyse the failure or defect, repair and return the circuit breaker to service, exclude deliberate delays," plus (2) "time required to get to site and obtain spare parts, exclude deliberate delays." This change in definition of "circuit breaker downtime" was made in the Second Enquiry because it was believed that some respondents in the First Enquiry may have misinterpreted what was asked for. However, it should be noted that deliberate delays for repair of the circuit breaker have been excluded in both enquiries when calculating "circuit breaker downtime."

4. RELIABILITY DATA FROM FIRST ENQUIRY

A total of 102 electric utilities from 22 countries submitted data on 20,000 circuit breakers above 63 kV. This included breakers of all technologies. Data were collected for the years 1974-77 on circuit breakers installed after January 1, 1964. This gave a total of 77,892 breakers-years of service during the four year period. This was a pioneering effort that required the development of: 1. reliability and maintenance definitions, 2. survey questionnaire, and 3. the method of analysis of the data. This encouraged utilities to develop a failure reporting system. Countries submitting data were: Australia, Belgium, Brazil, Canada, Czechoslovakia, Denmark, Finland, France, Federal Republic of Germany, Greece, Ireland, Italy, Japan, Morocco, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, United Kingdom, and Yugoslavia. The results from this First International Enquiry were published in "Electra" [1].

The failure rate and downtime data are summarized in Table 2 with the data for major failure rate and minor failure rate shown separately. Average downtime data and the median downtime data are given for major failures. Failure mode data were reported for 773 of the 1,231 major failures; and Table 3 gives the per cent in each failure mode. It is assumed that the percentage distribution of these failures can be applied to the total number of major failures in Table 2. The estimated average number of operating-cycles per year per circuit breaker are given in Table 4. The data in Tables 2, 3, and 4 have been used to separate out the major failures that occurred during a command to open or close from those that occurred without a command to open or close; and this has been used to calculate the reliability data that is given in Table 5. This data can be used in substation and system reliability studies and gives the average number of

TABLE 1 - CIRCUIT BREAKER RELIABILITY DEFINITIONS

1. FAILURE - Lack of performance by an item of its required functions.

Note: The occurrence of a failure does not necessarily imply the presence of a defect if the stress or the stresses are beyond those specified.

2. MAJOR FAILURE (OF A CIRCUIT-BREAKER) - Complete failure of a circuit-breaker which causes the lack of one or more of its fundamental functions.

Note: A major failure will result in an immediate change in the system operating condition; e. g., the backup protective equipment being required to remove the fault, or, will result in mandatory removal from service for non scheduled maintenance (intervention required within 30 minutes).

3. MINOR FAILURE (OF A CIRCUIT-BREAKER) - Failure of circuit-breaker other than major failure; or any failure, even complete, of a constructional element or a sub-assembly which does not cause a major failure of the circuit-breaker.

4. DEFECT - Imperfection in the state of an item (or inherent weakness) which can result in one or more failures of the item itself or of another item under the specific service or environmental or maintenance conditions for a stated period of time.

5. CIRCUIT-BREAKER DOWNTIME - Time from the discovery of the failure until the breaker is returned to service.

major failures per 10,000 open commands or close commands of the following failure modes: "does not open on command", "does not break the current", "does not close on command", "does not make the current." The data in Table 5 also show the major failure rate when there is no command to open or close. A footnote in Table 5 gives the data for the two failure modes: "closes without command" and "breakdown across open pole;" these major failure rates are very low, but may have a serious consequence when they occur on a power system.

5. RELIABILITY DATA FROM SECOND ENQUIRY

The enquiry includes the years 1988 thru 1991 and was limited to single pressure SF6 circuit breakers because most of the new circuit breakers at these voltage levels now being purchased by electric utilities use this technology. The questionnaire [4] was revised to be simpler than for the First Enquiry.

This paper is one of several final reports containing data collected for 1988 thru 1991 from 132 utilities in 22 countries on about 18,000 circuit breakers applied at 63 kV & above placed in service after January 1, 1978. There were a total of 70,708 breakers-years of service during the four year period. Countries submitting data were: Australia, Austria, Belgium, Brazil, Canada, Czechoslovakia, Finland, France, Germany, Italy, Japan, Netherlands, New Zealand, Norway, Paraguay, Rumania, Sweden, Switzerland, United Kingdom, United States of America, Union of Soviet Socialist Republics, and Yugoslavia.

Table 6 shows the major and minor failure rates separately. Average downtime data and the median downtime data are given for major failures. Failure mode data were reported for 471 of the 475 major failures; and Table 7 gives the per cent in each failure mode. The questionnaire [4] for the Second Enquiry contains the additional major failure mode "locking in open or closed position." A study of

this "locking" data indicates that about 13% were found during a command to open, about 37% were found during a command to close, and 50% were found by an alarm during normal service. The estimated number of operating-cycles per year per breaker are given in Table 8. The data in Tables 6, 7, and 8 have been used to separate out the major failures that occurred during a command to open or close from those that occurred without a command to open or close; this has been used to calculate the reliability data that is given in Table 9. This shows the average number of major failures per 10,000 open commands or close commands of: "does not open on command", "does not break the current", "does not close on command", "does not make the current." These final results in Table 9 from the Second Enquiry can be compared with Table 5 from the First Enquiry. A footnote in Table 9 gives the data for the two failure modes: "closes without command" and "breakdown across open pole;" these failure rates are very low, but may have a serious consequence when they occur on a power system.

6. COMPARISON OF RELIABILITY DATA BETWEEN THE FIRST AND SECOND ENQUIRIES

The final results from the Second International Enquiry for 1988 thru 1991 show that modern single-pressure SF6 circuit breakers applied at 63 kV & above have a major failure rate that is only 43% of that of older technology circuit breakers reported in the First International Enquiry for 1974-1977. The largest improvement has occurred at voltages above 200 kV where the reported major failure rates are less than one-third as much. The minor failure rates are slightly higher in the Second Enquiry.

It is believed that utilities do a better job of collecting failure data now than was done during the First Enquiry. The biggest improvement is believed to have occurred in the collection of data on minor failures.

The "estimated average number of operating-cycles per year per breaker" were 42 and 26.5 respectively from the Second and First International Enquiries. These values have an effect on the calculated probabilities of breaker major failures per operating command. The Second Enquiry calculated the average number of operating-cycles per year per breaker by weighting each breaker equally. This is a better method than used in the First Enquiry where each questionnaire answer was weighted equally, and some answers contained many more breakers than other answers. It is not believed that there has been a significant change in the number of operating-cycles per year per breaker between the First and Second Enquiries. If 42 operating-cycles per year per breaker had been used to calculate the probabilities of breaker major failures per operating command for the First Enquiry, the probabilities shown in Table 5 would have been lower by a factor of 1.58.

Tables 9 and 5 can be compared to show the number of major failures per 10,000 cycles, where a cycle is one open command plus one close command. For all voltages combined the Second Enquiry shows 0.829 versus 3.06 for the First Enquiry and is a factor of 3.7 lower. But 1.58 of this improvement is explained in the previous paragraph because of using an estimated average of 42 operating-cycles per year per breaker versus 26.5 from the First Enquiry; and 3.7 divided by 1.58 equals 2.33. Thus the number of major failures per 10,000 cycles has decreased by at least a factor of 2.33.

7. COMPARISON OF BREAKER DOWNTIME DATA PER MAJOR FAILURE BETWEEN THE FIRST AND SECOND ENQUIRIES

The Second Enquiry had an average downtime of 94.6 hours per major failure versus 81.6 in the First Enquiry. But the median downtime was only 10.0 hours in the Second Enquiry versus 12.0 in the First Enquiry. Both enquiries show a highly skewed distribution where a small number of long downtimes result in the average being between about seven to nine times larger than the median value. These results are similar to the preliminary results from the first two years of the Second Enquiry that were published at the 1991 Montreal Symposium on Electric Power Systems Reliability [5]. There was written discussion in the Montreal Proceedings that questioned these results[8]. In particular, they did not believe that modern SF6 breakers have a longer average downtime per failure than older technology breakers from the First Enquiry. A special detailed study has been made of the downtime data from the Second Enquiry. The increase in breaker downtime for SF6 single pressure breakers is primarily due to a much longer "time to obtain spare part." 64% of the 94.6 hours per failure of average breaker downtime for "all voltages combined" can be attributed to "time to obtain spare part." This would appear to be due to the policies of electric utilities on spare parts rather than the ability to repair the breaker. In approximately 9% of the reported cases the "time to obtain spare part" was longer than the breaker downtime; this would indicate that the breaker was often placed back in service or was replaced before the spare part was obtained. The special study also found that there does not appear to be any significant difference in the breaker downtime between metal-enclosed and non-metal-enclosed SF6 breakers.

Data were not collected in the Second Enquiry on the breaker downtime for minor failures. This data were collected in the First Enquiry; and the average was 30.0 hours per minor failure with a median of 6.0.

8. SUBSTATION AND SYSTEM RELIABILITY STUDIES

The data in Tables 5 and 9 are a credible source of data based upon a large sample size. They can be used in substation and system reliability studies. Very few reliability studies use all of the breaker failure modes given in this data. The circuit breaker is the most difficult component to handle when making substation or system reliability studies because of the many different breaker functions and the associated failure modes.

λ_5 is the major failure rate without a command to operate. 63% of these failures for all voltages combined include the failure modes: alarm-locking in open or closed position, fails to carry the current, other requiring manual removal from service within 30 minutes. These might be assumed to be passive failures. The other 37% might be assumed to be active major failures (breakdown to earth, breakdown between poles, breakdown across open pole, closes without command, opens without command).

$c \cdot \lambda_c$ is the major failure rate during commands to operate, either for switching or to remove faults.

$\lambda_{c1} + \lambda_{c2}$ is the probability of not opening on command or not breaking the current during manual or automatic opening to perform switching or to remove a fault. This could be considered the breaker stuck closed probability.

$\lambda_{c3} + \lambda_{c4}$ is the probability of not closing on command or not making the current during manual or

TABLE 2 - FAILURE RATES AND DOWNTIME DATA FOR HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 KV (from CIGRE 13-06 Working Group First International Enquiry, 1974-1977, All Interrupting Technologies)

---MAJOR FAILURE RATES---			---MINOR FAILURE RATES---		
Sample Size	Major Failures per Breaker Year	Hours Downtime per Failure Average Median	VOLTAGE kv	Sample Size Breaker of Years Failures*	Failures* per Breaker Year
77,892	1,231**	81.6	All Voltages	46,272	1,641
33,877	138	29.3	63 ≤ V < 100	24,716	409
26,743	437	94.4	100 ≤ V < 200	13,915	581
9,939	257	58.5	200 ≤ V < 300	5,614	359
6,224	283	83.8	300 ≤ V < 500	1,682	275
1,109	116	142.0	500 ≤ V	345	17

CODE

* Minor failures plus defects

** 45 of the 1,231 major failures had a fire and/or explosion
 *** Downtime includes: time required to get to site, analyse the failure, obtain spare parts, repair and return circuit breaker to service. Belliberate delays have been excluded.

TABLE 3 - MAJOR FAILURE MODES OF HIGH-VOLTAGE CIRCUIT BREAKERS (from CIGRE 13-06 WG First International Enquiry, 1974-1977, All Interrupting Technologies)

All Volt.	63 V < 100	100 V < 200	200 V < 300	300 V < 500	500 V
33.7	34.1	38.0	31.4	29.6	33.3
14.1	10.1	11.7	17.5	17.4	25.0
1.7	2.8	0.7	2.7	1.3	0
5.2	4.5	4.4	7.2	4.3	16.7
1.6	0.6	0.7	4.0	1.3	0
1.9	1.1	1.8	0.9	3.5	0
2.5	1.1	2.9	1.3	4.3	0
1.3	1.7	1.5	1.3	0.9	0
1.3	1.7	0.7	1.3	1.7	0
0	0	0	0	0	0
0.5	0.6	0.7	0	0	0
4.0	2.7	6.2	3.6	1.7	8.3
1.2	0	2.2	0.4	1.3	0
31.0	39.0	28.5	28.4	32.7	8.4
773	138	274	172	179	10

Number of answers

TABLE 4 - ESTIMATED AVERAGE NUMBER OF OPERATING-CYCLES PER YEAR PER BREAKER (from CIGRE 13-06 WG First International Enquiry, 1974-1977, All Technologies)

ALL VOLT. 63 kv < 100		100 kv < 200		200 kv < 300		300 kv < 500		500 kv < 800	
NUMBER OF ANSWERS		422		75		151		72	
AVERAGE	26.5	24.7	23.8	32.0	32.0	25.0	26.8	26.8	26.8
10% PERCENTILE	3.3	3.3	3.1	3.4	3.4	5.0	5.0	5.0	5.0
25% PERCENTILE	6.3	4.0	6.5	8.7	8.7	7.3	7.3	7.3	7.3
MEDIAN	13.1	8.2	12.0	14.7	14.7	15.7	15.7	15.7	15.7
75% PERCENTILE	28.8	29.4	24.0	31.1	31.1	38.6	38.6	38.6	38.6
90% PERCENTILE	53.1	40.4	36.8	71.1	71.1	67.0	67.0	67.0	67.0
95% PERCENTILE	78.0	55.4	54.7	138.7	138.7	73.0	73.0	73.0	73.0
MAXIMUM	548.6	491.2	548.6	381.6	381.6	85.4	85.4	85.4	85.4

TABLE 5 - RELIABILITY DATA ON HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 KV THAT CAN BE USED IN SYSTEM RELIABILITY STUDIES... (from CIGRE 13-06 Working Group First International Enquiry 1974-1977, All Interrupting Technologies)

- Major Failures per Open Command $\lambda_{c1} + \lambda_{c2}$
- Major Failures per Close Command $\lambda_{c3} + \lambda_{c4}$
- Major Failures per Cycle** $\lambda_c = \lambda_{c1} + \lambda_{c2} + \lambda_{c3} + \lambda_{c4}$
- Average Number of Cycles** per Year C
- Major Failures per Breaker-Year During Commands to Open or Close C. λ_c
- Major Failures per Breaker-Year Occurring Without A Command to Open or Close λ_s
- Total Major Failures per Breaker-Year $\lambda_M = \lambda_s + C.\lambda_c$

λ_{c1}	λ_{c2}	λ_{c3}	λ_{c4}	λ_c	C	C. λ_c	λ_s	λ_M
Does Not Open On Command PER 10,000	Does Not Break Current PER 10,000	Does Not Close On Command PER 10,000	Does Not Make the Current PER 10,000	Major Failures per 10,000 Cycles**	Average Number of Cycles** per Year	Major Failures per Year	Major Failures per Year	Total Major Failures per Year
0.84	0.11	2.01	0.10	3.06	26.5	All Volt.	.0077***	.0158
0.166	0.018*	0.562	0.010*	0.756	24.7	63 V < 100	.0022	.0041
0.81	0.12*	2.60	0.05*	3.58	23.8	100 V < 200	.0078	.0163
1.42	0.07*	2.54	0.32*	4.35	32.0	200 V < 300	.0119	.0258
3.16	0.64*	5.39	0.24*	9.43	25.0	300 V < 500	.0236	.0455
9.75*	0.00*	12.98*	0.00*	22.73*	26.8	500 V	.0609	.1045

CODE

* Small sample size in failure mode data - less than 8 failures

** A cycle is one open command and one close command

*** Approximately 10.7% of these major failures are "breakdown across open pole" and another 3.5% are "closes without command"

**** Calculated from Tables 2, 3 and 4

TABLE 8 - ESTIMATED AVERAGE NUMBER OF OPERATING-CYCLES PER YEAR PER BREAKER
(Final Results from CIGRE 13-06 WG Second International
Enquiry on SF6 Single-Pressure Circuit Breakers 1988-1991)

NUMBER OF BREAKERS	ALL VOLTS. 63kV<100 100kV<200 200kV<300 300kV<500 500kV					
	64,676	20,716 21,309 10,657 9,594 2,400				
AVERAGE	42	47	40	39	36	45
10% PERCENTILE	13	24	10	19	13	12
25% PERCENTILE	20	32	20	20	16	28
MEDIAN	20	48	25	20	20	44
75% PERCENTILE	50	50	46	25	33	60
90% PERCENTILE	76	84	60	55	82	68
95% PERCENTILE	84	84	96	100	89	72
MAXIMUM	1760	450	620	1600	1760	199

TABLE 9 - RELIABILITY DATA ON SINGLE-PRESSURE HIGH VOLTAGE CIRCUIT
BREAKERS APPLIED ABOVE 63 kV THAT CAN BE USED IN SYSTEM RELIABILITY STUDIES****
(Assumes that 13% of the "Locking" Failures Occurred After a Command to Open
and Another 37% of the "Locking" Failures Occurred After a Command to Close)

1. Major Failures per Open Command $\lambda_{c1} + \lambda_{c2}$
2. Major Failures per Close Command $\lambda_{c3} + \lambda_{c4}$
3. Major Failures per Cycle** $\lambda_c = \lambda_{c1} + \lambda_{c2} + \lambda_{c3} + \lambda_{c4}$
4. Average Number of Cycles** per Year C
5. Major Failures per Breaker-Year During Commands to Open or Close C· λ_c
6. Major Failures per Breaker-Year Occurring Without A Command to Open or Close λ_s
7. Total Major Failures per Breaker-Year $\lambda_M = \lambda_s + C \cdot \lambda_c$

λ_{c1} Does Not Open On Command PER 10,000 MAJOR FAILURES	λ_{c2} Does Not Break the Command PER 10,000 MAJOR FAILURES	λ_{c3} Does Not Close On Command PER 10,000 MAJOR FAILURES	λ_{c4} Does Not Make the Command PER 10,000 MAJOR FAILURES	λ_c Major Failures per 10,000 Cycles**	C Average Number of Cycles** per Year	C· λ_c Major Failures per Year	λ_s Major Failures per Year	λ_M Total Major Failures per Year
0.192	0.048	0.562	0.027	0.829	42.	34.216	.00324***	.00672
0.077	0.000*	0.167	0.009*	0.253	47.	11.941	.00156	.00275
0.161	0.043*	0.781	0.000*	0.985	40.	39.400	.00394	.00680
0.229	0.071*	0.648	0.095*	1.043	39.	40.617	.00407	.00814
0.524	0.113*	1.071	0.057*	1.765	36.	63.540	.00635	.01210
0.506*	0.336*	0.951	0.112*	1.905	45	85.725	.00857	.01967

CODE
* Small sample size in failure mode data - less than 8 failures
** A cycle is one open command and one close command
*** Approximately 10.6% of these major failures are "breakdown across open pole" and another 2.2% are "closes without command"
**** Calculated from Tables 6, 7 and 8 - final results from CIGRE 13-06 WG Second International Enquiry for 1988-1991.

TABLE 6 - FAILURE RATES AND DOWNTIME DATA FOR SINGLE-PRESSURE
HIGH-VOLTAGE CIRCUIT BREAKERS APPLIED ABOVE 63 kV
(Final Results from CIGRE 13-06 Working Group
Second International Enquiry, 1988-1991)

Number of Major Failures	λ_M Major Failures per Breaker Year	FAILURE RATES		
		Hours Downtime per Failure Average Median	Sample Size Breaker Years	Failures* per Breaker Year
475**	.00672	94.6	70,708	.0475
67	.00275	39.1	24,355	.0223
160	.00680	51.1	23,520	.0475
89	.00814	54.6	10,913	.0697
120	.01210	162.5	9,917	.0776
39	.01967	209.4	1,983	.0837

CODE
* Minor failures plus defects
** 31 of the 475 major failures had a fire and/or explosion
*** Downtime includes: time from discovery of the failure until the breaker is returned to service, exclude deliberate delays.

TABLE 7 - MAJOR FAILURE MODES OF
SINGLE-PRESSURE SF6 HIGH-VOLTAGE
CIRCUIT BREAKERS (Final Results
from CIGRE 13-06 WG Second
International Enquiry, 1988-1991)

ALL VOLT.	63 kV<100	100 kV<200	200 kV<300	300 kV<500	500
24.63	25.37	31.65	19.32	21.01	17.95
8.28	11.94	4.43	6.82	11.76	10.26
1.06	0.00	1.90	2.27	0.00	0.00
7.03	10.45	5.06	7.95	9.24	0.00
1.70	1.49	0.00	4.55	1.68	2.56
2.97	0.00	2.53	3.41	3.36	7.69
1.49	0.00	1.90	1.14	2.52	0.00
3.18	2.99	0.63	4.55	4.20	7.69
1.49	0.00	0.63	0.00	5.04	0.00
3.61	10.45	1.90	3.41	1.68	5.11
1.49	4.48	0.00	2.27	0.94	2.56
28.45	8.96	38.61	31.82	29.41	10.26
14.65	23.88	10.76	12.50	9.24	35.90
471	67	158	88	119	39

Does not close on command
Does not open on command
Closes without command
Opens without command
Does not make the current
Fails to carry the current
Breakdown to earth
Breakdown between poles
Breakdown across open pole (internal)
Breakdown across open pole (external)
Locking in open or closed position
Other

automatic closing or reclosing. This could be considered the breaker stuck open probability.

The dominant breaker failure mode is "does not close on command" and should not be neglected in substation or system reliability studies. This failure mode: 1. can prevent equipment from being switched into service when needed, 2. can cause a transient line outage to become a permanent outage, or 3. can cause an outage of a line or generator to be extended beyond the normal outage time.

The failure mode "closes without command" has a very low failure rate. But its occurrence sometimes results in all of the back up protection being defeated and in some cases has been the cause of major blackouts. The failure mode "breakdown across open pole" has the highest electrical failure rate of the main interrupter; and back up protection must operate to remove the fault. The failure rates of "closes without command" and "breakdown across open pole" are both very low; but they can be larger than the double contingency failure rates typically calculated for other component combinations in a substation reliability study.

None of the substation reliability analysis papers sponsored by CIGRE Study Committee 23 in recent years [8][9][10] have used all of the breaker failure modes given in Tables 5 and 9.

The written discussions on the four substation reliability papers from Session 2 in the Proceedings of the Montreal 1991 CIGRE Symposium [11] pointed out that existing methods of substation reliability analysis had a credibility problem; this included both the models used and the reliability data used. One model used circuit breaker failure rates that were between 6 to 500 times too high. None of the models included several of the pertinent breaker failure modes; such as, does not close on command, breakdown across open pole, closes without command. Only one of the four models included taking the electrical equipment in and out of service for scheduled maintenance; and this occurs much more frequently than the breaker operating to remove line or equipment faults. Only one of the four models included the frequency of both transient faults and permanent faults on the connected lines. Breaker downtimes used were an order of magnitude too low.

9. CONCLUSIONS

CIGRE 13.06 Working Group has collected and analysed world wide reliability data on high voltage circuit breakers applied on networks at 63 kV & above. These data are a large sample size and can be useful in substation and system reliability studies. Two important contributions to the knowledge of circuit breaker reliability are: (1) the failure mode data, and (2) the calculations of probabilities of not responding properly to an operating command to open or to close. The 1974-1977 data can be used for older technology circuit breakers, and the 1988-1991 data show the improvement that has been achieved with new technology single-pressure SF6 breakers. The major failure rate for modern SF6 single-pressure breakers is only about 43% as much as older technology breakers, and for voltages above 200 kV it is only one-third as much. Substation and system reliability studies should pay attention to this improvement. The lower major failure rate of circuit breakers may influence both the lay-out of primary plant and secondary systems.

Improved access to spare parts by utilities could significantly improve breaker availability by reducing the downtime after major failures.

The circuit breaker is the most difficult component to handle when making substation or system reliability studies because of the many different breaker functions and the associated failure modes. The data on breaker failure modes and failure probabilities will enable better models to be developed for use in substation and system reliability studies. Better data and better models have both been needed in order to improve the credibility of these studies.

The circuit breaker reliability definitions that were first written in 1971 are now accepted and used world-wide. Thus it is logical that these definitions become standards of the International Electrotechnical Commission (IEC). It is recommended that these circuit breaker reliability definitions become included in a standard under IEC Technical Committee No. 17 on Switchgear and Controlgear and that the existing technical report IEC 1208 (1992) "Guide for High-Voltage AC Circuit Breaker Maintenance" be upgraded to an IEC standard after the three year trial period is completed.

REFERENCES

1. G. Mazza, R. Michaca, "The First International Enquiry on Circuit Breaker Failures & Defects in Service," ELECTRA No. 79, Dec 1985, pp 21-91.
2. R. Michaca, C. R. Heising, G. Koppl, "Summary of CIGRE Working Group 13-06 Studies on the Test and Control Methods Intended to Assure the Reliability of High Voltage Circuit Breakers." ELECTRA No. 102, Oct 1985, pp 133-175.
3. J. Beierer, R. Kearsley, J. Verdon, "Maintenance of Modern High Voltage Circuit Breakers," ELECTRA No. 102, Oct 1985, pp 119-130.
4. A. Bargigia, C. R. Heising, A.L. J. Janssen, J. Maaskola, R. Michaca, "Interim Report on the Second International Enquiry of the Reliability of High-Voltage Single Pressure SF6 Circuit Breakers," Paper No. 23-107, CIGRE, Aug 27-Sept 1, 1990, Paris.
5. A. Bargigia, W. Degen, C. R. Heising, M. Ishikawa, A. L. J. Janssen, J. E. Maaskola, R. Michaca, M. Tudrej, "High-Voltage Circuit Breaker Reliability Data for Use in System Reliability Studies - Interim Report. CIGRE 13-06 Working Group," Paper No. 2-01, CIGRE Symposium on Electric Power Systems Reliability, Sept 16-18, 1991, Montreal.
6. A. L. J. Janssen, W. Degen, M. Tudrej, S. Ikeda, "Diagnostic Techniques for High Voltage Circuit Breakers and Their Applications," CIGRE Symposium on Diagnostic Techniques, April 19-21, 1993, Berlin
7. A. L. J. Janssen, W. Degen, C. R. Heising, H. Bruvik, E. Colombo, W. Lanz, P. Fletcher, G. Sanchis, "A Summary of the Final Results and Conclusions of the Second International Enquiry on the Reliability of High Voltage Circuit-Breakers," Paper No. 13-20x, CIGRE, Aug 28-Sept 3, 1994, Paris
8. J. Declerq et al, "Substation Reliability Comparison of Two Methods," ELECTRA No. 99, March 1985.
9. B. G. Anderson et al, "Reliability of HV Substations with Special Regard to the Secondary Equipment," ELECTRA No. 111 March 1987, pp 17-23.
10. 1980 CIGRE Papers No. 23-01, 23-05, and 23-08.
11. Proceedings of the CIGRE Symposium on Electric Power Systems Reliability, Session 2, "Impact of Reliability of Components on System Reliability," Sept 19-21, 1991, Montreal, pp 57-70.

Le CIGRÉ a apporté le plus grand soin à la réalisation de cette brochure thématique numérique afin de vous fournir une information complète et fiable.

Cependant, le CIGRÉ ne pourra en aucun cas être tenu responsable des préjudices ou dommages de quelque nature que ce soit pouvant résulter d'une mauvaise utilisation des informations contenues dans cette brochure.

Publié par le CIGRÉ
21, rue d'Artois
FR-75 008 PARIS
Tél. : +33 1 53 89 12 90
Fax : +33 1 53 89 12 99

Copyright © 2000

Tous droits de diffusion, de traduction et de reproduction réservés pour tous pays.

Toute reproduction, même partielle, par quelque procédé que ce soit, est interdite sans autorisation préalable. Cette interdiction ne peut s'appliquer à l'utilisateur personne physique ayant acheté ce document pour l'impression dudit document à des fins strictement personnelles.

Pour toute utilisation collective, prière de nous contacter à sales-meetings@cigre.org

The greatest care has been taken by CIGRE to produce this digital technical brochure so as to provide you with full and reliable information.

However, CIGRE could in any case be held responsible for any damage resulting from any misuse of the information contained therein.

*Published by CIGRE
21, rue d'Artois
FR-75 008 PARIS
Tel : +33 1 53 89 12 90
Fax : +33 1 53 89 12 99*

Copyright © 2000

All rights of circulation, translation and reproduction reserved for all countries.

No part of this publication may be produced or transmitted, in any form or by any means, without prior permission of the publisher. This measure will not apply in the case of printing off of this document by any individual having purchased it for personal purposes.

For any collective use, please contact us at sales-meetings@cigre.org