Optimization of maintenance, diagnostic technique and design of substation equipment based on analysis of service experience

C. Neumann, B. Rusek
RWE Transportnetz Strom, Dortmund

G. Balzer
Technical University of Darmstadt

Germany

SUMMARY

Changes in the regulatory framework of the electricity market have intensified the efforts of the grid operators for optimized exploitation of their networks and the equipment installed. In this connection, maintenance and lifetime as well as reliability aspects are of particular interest. To cope with these challenges, a thorough analysis of the service experience is necessary. The results are the feed back for the optimization of the maintenance procedures and methods and for a qualified assessment of lifetime. Furthermore, the results are the basis for the development of adequate monitoring and diagnostic techniques. Finally, the results are used for design improvements and optimization.

The paper describes the above mentioned analysis of service experience for different substation equipment, like circuit-breaker and instrument transformers, and for gas-insulated substations (GIS). It will be shown which consequences can be drawn with respect to optimization of maintenance activities and lifetime assessment. Regarding monitoring and diagnostic techniques the main important diagnostic indicators are identified and possible diagnostic methods are presented. At least some examples of design improvements and design optimization measures on circuit-breakers, instrument transformers and GIS are given, some of them have become standard solutions meanwhile.

KEYWORDS

Maintenance, lifetime, equipment, substation, service experience

claus.neumann@rwe.com

1. *Introduction*

Due to the regulatory changes in the political and economical framework of the electricity market, the power system operator is obligated to assure the high reliability of electrical energy supply at simultaneous reduction of the own operational costs. These requirements can be achieved by an optimization of the maintenance activities and by application of equipment with high reliability and by design improvements. It is obvious, that the service experience and a thorough analysis is the best basis for the optimization process in question. The following considerations are related to substation equipment – circuit breakers (CB) and instrument transformers – as well as to gas-insulated substations (GIS).

2 *Service experience with circuit breakers and consequences with respect to optimization*

2.1 *Self-blast breakers*

Since the early 1990th CB technology has moved to self-blast breakers mainly with spring drive mechanisms. Therefore it is of big interest, to evaluate the service experience collected with this technology systematically and to use the knowledge gained for optimization and further development.

In Fig. 2.1 self-blast CBs with spring drive and 31.5 kA rated short-circuit breaking current of two different manufacturers are considered. The population of CBs under consideration is divided in two years periods and for each period the average failure rate is determined. The average failure rate is defined as the ratio of the number of failures to the sum of CB years. Thereby, the failures (or irregularities) are divided into two categories – failures occurred during operation and failures detected during inspection. The failures during operation mostly result in reduced functional performance. The second category can be identified during maintenance actions (e.g. visual inspections). These irregularities impair one of the breaker functions in closer not defined time (e.g. small leakages) or in case of CB switching (e.g. defect of SF6 density gauge would block the tripping signals). This failure would have been classified to failures during operation after having received a tripping signal. However, the irregularity was identified thanks inspection before a tripping signal came. For this reason, it is classified to failures detected during inspection.

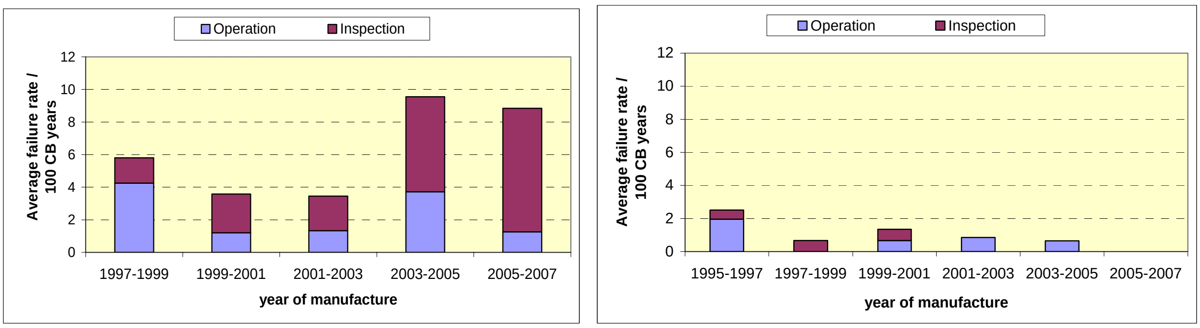

Fig. 2.1: Average failure rate of 110 kV SF6 self blast circuit breakers depending on the year of manufacture

a) 437 breakers of type A b) 349 breakers of type B

The average failure rates of CBs of type A are significantly higher than those of type B. Moreover, the failure rate of type A has increased in the last years, which is an indication of quality deficiencies in the manufacturing process. The first manufacturing series of type B exhibits failure rates distinctly above the average. The decrease in the following years shows that the manufacturer evidently improved the manufacturing and quality assurance process and removed the weak components as well causing failures in previous years.

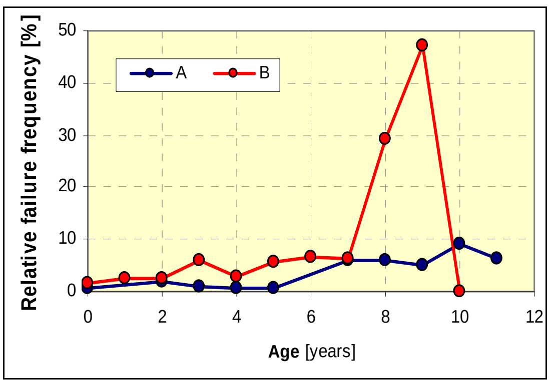

Fig. 2.2: Relativ failure frequency for self blast circuit breaker type A and B

The consideration of failure frequency depending on time (Fig. 2.2) shows a similar relative failure frequency for both types of CBs up to the 7th year of operation. Every data point gives the ratio of number of failures at the relevant age of the CB related to the number of CBs as old or older than the CB in question. After that a distinct increase can be observed for breaker type A which reaches its maximum in 9th year of operation. The maximum is an effect of the maintenance activities that according to the company policy were carried out in an 8 years interval on both CB types. However, the CBs of type B show in this period a very small increase of failure frequency, only. Due to small initial failure rates, the causes of failures classified to “teething” failures can obviously be neglected. From Fig. 2.2 one can conclude that the altering processes for CBs type A develop faster than for type B.

Such high number of failures found during the maintenance periods would require an adjustment of the maintenance period depending on the reliability the grid operator wants to assure. For breakers type A maintaining or even shorting of the maintenance periods can be considered, while for breakers type B extending of the maintenance periods seems reasonable. However, such decisions have to be taken very carefully. It might be possible for instance that after the maintenance actions and removal of the faulty components the failure frequency drops down and remains on this level. While for CBs of type B the failure frequency might slightly increase with time [1]. Such scenario is less probable but it has to taken into account.

An important task is avoiding failures during operation by monitoring improvements. For that purpose the failures were subdivided according to the main functional groups [2]. The failures observed in the control and auxiliary circuits are difficult to identify by monitoring devices. However, most failures of that type are easily detectable by visual inspections. That is also true for failures of group “Others” in Fig. 2.3a [3]. The majority of failures of the breaker type B occurred in group “Insulation”. These failures can successfully be identified in advance by a SF6 density gauge, which is already installed in the CB. Concluding, the major sources of failures can be identified with simple and effective methods like visual inspections or SF6 density monitoring. Therefore, it has to be discussed very thoroughly how far additional expenditure for sophisticated monitoring devices can be justified from the economical point of view and with regard to improved reliability [4].

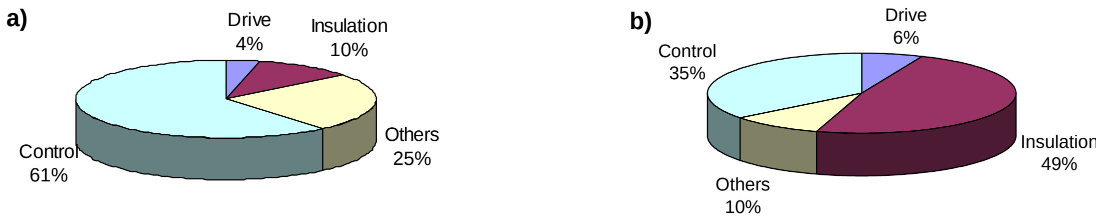

Fig. 2.3: Failure distribution on main functional groups of circuit breakers
a) type A (112 failures) b) type B (21 failures)

Taking into consideration the failure rates and their trends it can be concluded that CB type A needs more overall improvements to obtain the same reliability as CB type B. This is at least also of interest from the economical point of view, since less failures also means less expenditure and less dispatching efforts.

2.2 Self-blast technology in comparison with puffer technology

Due to expensive maintenance and insufficient switching capability minimum oil and air blast CBs are continuously replaced by the newest technology, i.e. self-blast CBs. It can be expected that in the next 10 years the minimum oil and air blast technology will fully be replaced, predominantly by SF6 self-blast CBs. Therefore a comparison of SF6 CBs of the first and the last generation, i. e. puffer type and self-blast type breakers is of interest.

Fig.2.4 shows the relative failure frequency in % (or per 100 CBs) of SF6 puffer and self-blast CBs respectively. Thereby, the failures (or irregularities) are categorized again into failures occurred during operation and failures detected during inspection. Additionally trend lines are given established by linear regression. The steepness of the regression curve is a measure of the ageing effects .

Although the self-blast CBs are much younger than the puffer CBs, their trend lines show a higher steepness (a_i=0.30 and a_o=0.25 compared to a_i= 0.18 and a_o=0.15 of the puffer CBs). From these figures one could conclude that the breakers of the newer technology might reach faster the end of service life than the CBs of the older type. However, it has to be taken into account that the failure statistics of self-blast CBs are related to a shorter time period and additionally one extended maintenance only was carried out on these breakers. The consideration of puffer CBs namely shows that the relative frequency of failures detected during inspection significantly decreases after the first extended maintenance after about 6 years (Fig. 2.4 a). That might indicate that a lot of “teething” failures were removed at the first extended maintenance.

The interpretation for the distinct increase of failures on self-blast CBs occurred during operations after 8 years (Fig. 2.4 b) can be twofold: Either the maintenance before had been carried out improperly or some of the failures could not be detected with the method used. In order to avoid both types of failures the maintenance actions can be supported a by a mobile diagnostic system enabling more detailed and qualified diagnostic results [5].

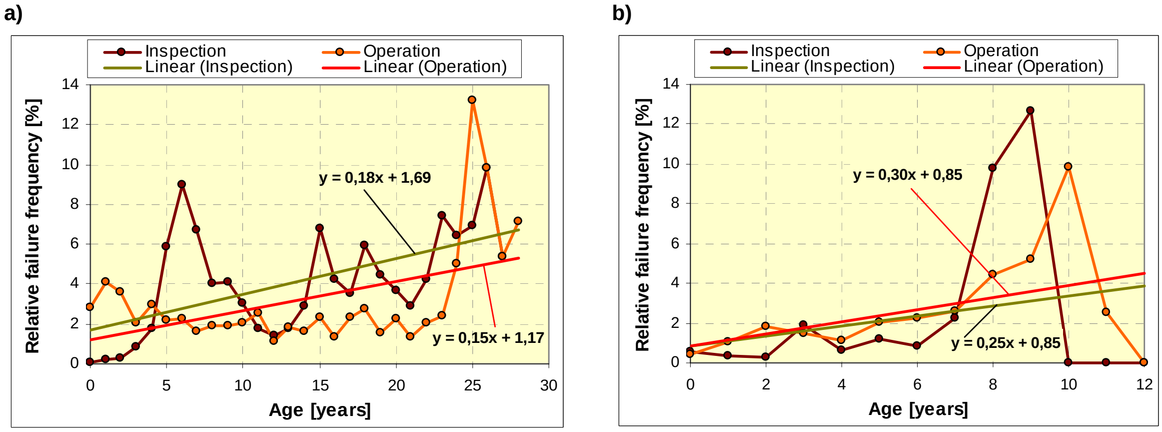

Fig. 2.4: Relative failure frequency of 110 kV SF6 circuit breakers
a) puffer type b) self-blast type

The failure distribution of 110 kV self-blast and puffer type CBs with regard to the main functional groups is shown in Fig. 2.5. Here again, it has been differentiated between failures occurred during operation and those detected during inspection.

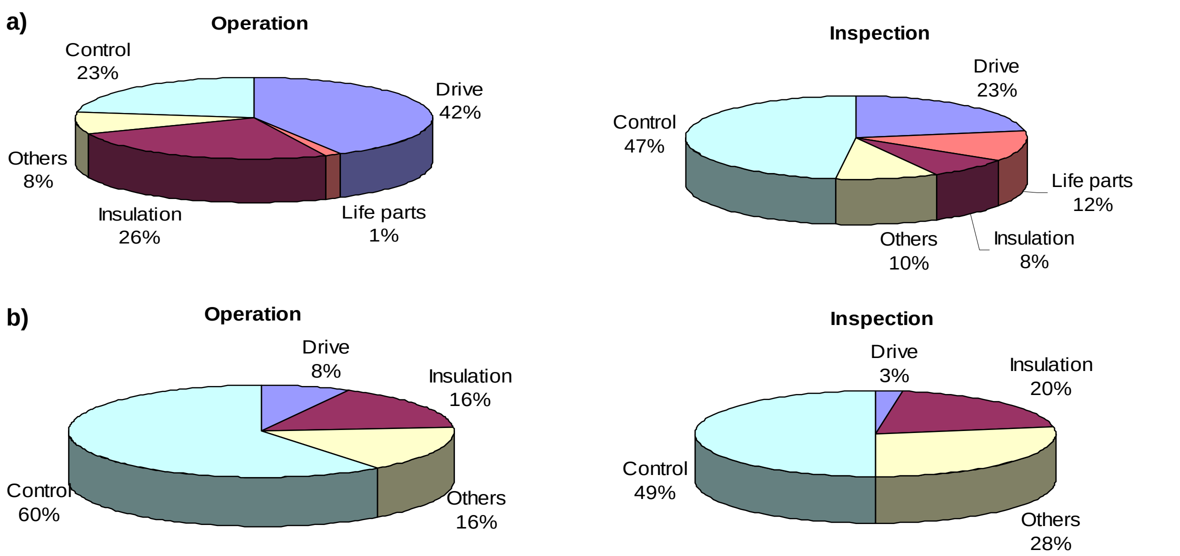

Fig. 2.5: Failures occurred during **operation** and detected during **inspection** for 110 kV SF6 circuit breakers
a) puffer type b) self-blast type

The distribution of failures significantly differs depending on the breaker type. The events of type "Others" and "Control" are quite easy to overcome [4]. The events in remaining domains require usually much longer repair times and higher expenditures. Important to notice is, that the events found during maintenance are partly connected with some small irregularities that could lead to a major failure [2]. Moreover, the diagrams above are dominated by the design and drive type of the CB. Whereas the puffer CBs in majority have hydraulic drives, the self-blast breakers are equipped with spring drives. The newer technology exhibits less failures in operating mechanisms. However, it is dominated by failures in control and by other less important irregularities.

2.3 Puffer type technology (1st and 2nd generation)

In the past, for interruption of high short-circuit currents puffer type technology was primarily applied. These breakers were mainly driven by hydraulic operating mechanisms mostly with nitrogen energy storage or partly spring storage devices. Since the most part of these breakers are installed in important substations with regard to system security, the reliability of these breakers to be expected in the future is a significant subject. For this reason, the service experience with those CBs is considered more in details.

Fig. 2.6 shows the average failure rate for 380 kV CBs of the 1st and 2nd generation respectively. In the first periods after introduction the failure rates for CB's of the 1st generation are double as high as for the 2nd

generation. From that, particularly from the reduction of failures occurred during operation one can conclude that manufacturing improvements have been achieved with the 2nd generation. However, the failure rate in following periods increases which means that the quality standard could not be maintained. The reason for that might be the necessity of material and manufacturing cost reduction caused by a stronger competition.

a) b)

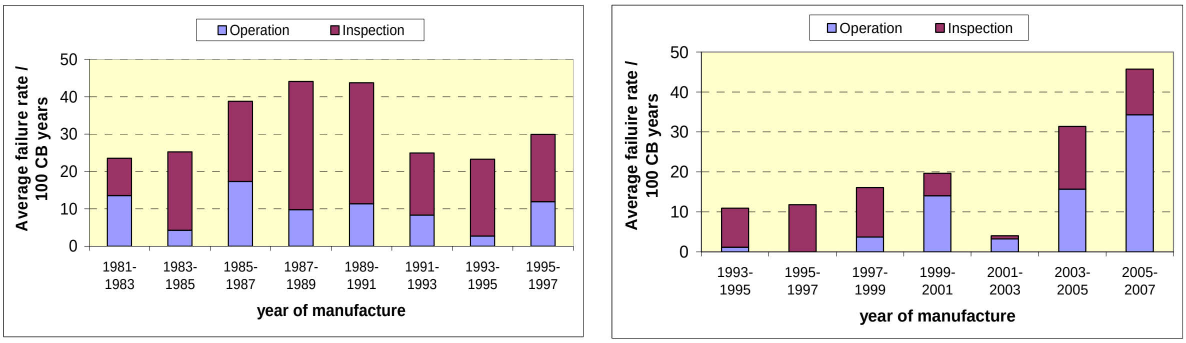

Fig. 2.6: Average failure rate for 380 kV circuit breakers
a) 1st generation b) 2nd generation

The failure frequency of CBs of the 1st generation (Fig. 2.7 a) remains below 10% until 20th year of operation. Afterwards the failure frequency increases rapidly reaching its maximum of 55% in the 25th year of operation. The number of failures that were detected during inspections also increases with the age of breakers. Assuming, that the regression curves show the correct development of ageing effects, it can be expected that in the next 10 to 15 years the 1st generation of CBs will have to be replaced. In order to sustain a high degree of reliability of these breakers until they will be replaced, the grid operator has to count with additional expenditures for maintenance and repair.

a) b)

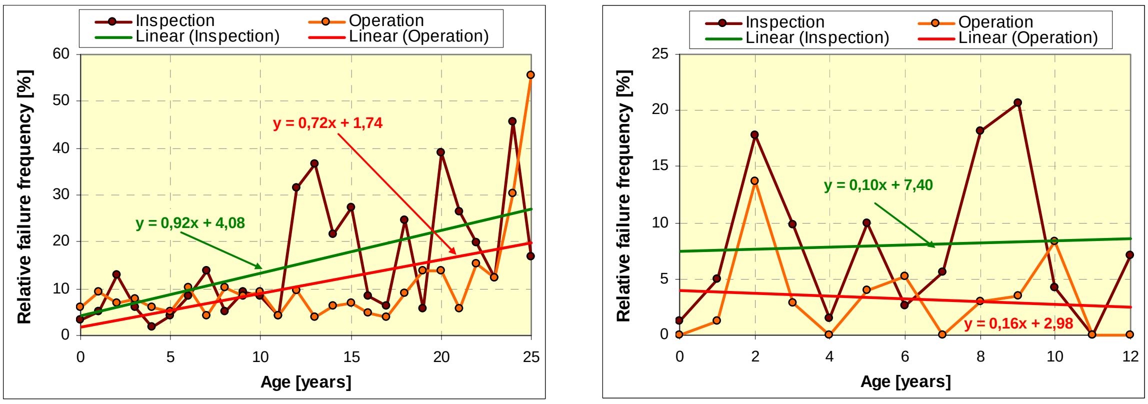

Fig. 2.7: Relative Failure frequency for 380 kV circuit breakers
a) 1st generation b) 2nd generation

The failure frequency for CBs of the 2nd generation (Fig. 2.7 b) decreases with time. The peak during the second year is nevertheless interesting. At this time an additional inspection of the CB is performed before the warranty of usually 2 years expires. An increase of the failure frequency during operation points to “teething” failures. The next increase of failures detected during inspection is connected with the maintenance strategy of the grid operator which requires for extended maintenance every 8 years. Obviously for some CBs the maintenance actions were postponed in the next year, since the equipment could not be de-energized in time due to increased load flow. Hence it can be concluded, that the failure frequency found during inspections should be in the 8th year much higher, if the maintenance actions would be carried out in time. Faced with this fact, an extension of the maintenance intervals, as it was discussed, should not be taken into consideration for the breaker type in question.

3. *Service experience with instrument transformer and conclusions for improvements of design and substation layout*

Although instrument transformers are very reliable pieces of equipment, failures have to be studied very thoroughly, since failure events mostly are very spectacular and affect further substation equipment.

Fig. 3.1 shows that nearly 50% of the failures experienced with HV instrument transformers for outdoor application are caused by electrical overstressing. Mainly two failures causes are dominant: stresses by lightning overvoltages and thermal and partly dielectric stresses due to ferro-resonances.
Failures due to lightning overvoltages mainly occurred on SF6 gas insulated instrument transformers, but sometimes even on oil immersed equipment. By more sophisticated investigations by means of simulations and laboratory test it was found out that this problem is mainly caused due to insufficient insulation coordination [6].

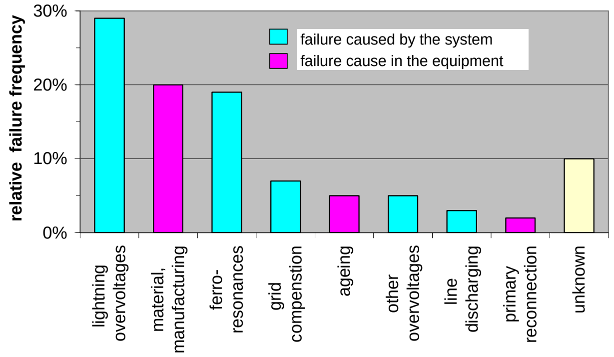

Fig. 3.1: Main failure causes on instrument transformers

In cases of steep front overvoltages with a steepness above 0.5 MV/µs, as they occur due to first and subsequent lightning strokes to the overhead lines in the vicinity of the substation, the lightning withstand voltage of the instrument transformer as well as of the switching gap of the CB will be exceeded (Fig. 3.2). The problem could be solved by improved overvoltage protection measures by installation of arresters at the line entrance of the feeder. Due to the lack of space in the substation the arrester was integrated into the line disconnector [7]. This integration was verified using the arrester as one post insulator of the two column disconnector. A sufficient mechanical strength of the arrester for this function was proven by tests of the bending strength of the porcelain hollow insulator. The grading electrode turned out to be necessary for a sufficiently uniform voltage distribution had to be adjusted for this special application (Fig. 3.3).

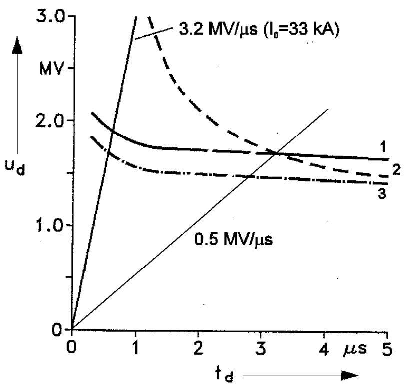

Fig. 3.2: Voltage-time characteristic
(1) switching gap of CB (2) spark gap
(3) instrument transformer

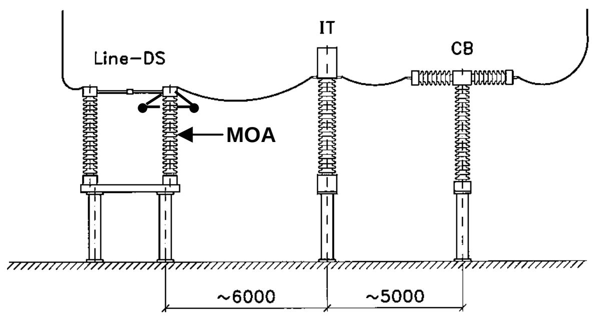

Fig. 3.3: 380 kV feeder arrangement consisting of line disconnector, instrument transformer and two unit circuit breaker

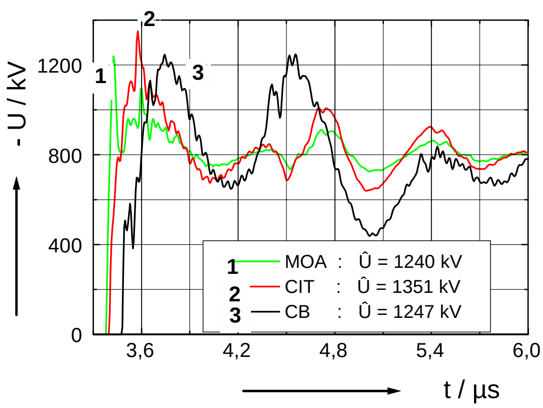

Fig. 3.4: Overvoltages at metaloxide arrester (MOA), combined instrument transformer (CIT) and circuit-breaker (CB) due to a subsequent stroke with ~90 kA/µs

The results given in Fig. 3.4 demonstrate that the overvoltage protection measures considered are suited to protect the instrument transformer as well as the switching gap of the circuit-breaker even in case of steep front overvoltages. Since the strength of SF6 gas insulated systems at lightning overvoltages is strongly affected by protrusions even in the mm-range, it was decided to test the SF6 gas insulated instrument transformers with lightning impulse voltage as routine test.

The secondly frequent failure cause is over-stressing due to ferro-resonance phenomena. There are various configuration which can lead to ferro-resonances [8]. One configuration typical for systems where multi-circuit arrangements are applied, is given in Fig. 3.5. De-energizing the 110 kV circuit oscillation due to ferro-resonances may be excited in the voltage transformers at the line entrance. The damping of these oscillations might be insufficient, since the circuit is further on fed by capacitive coupling from the energized 220 kV or 380 kV circuits.

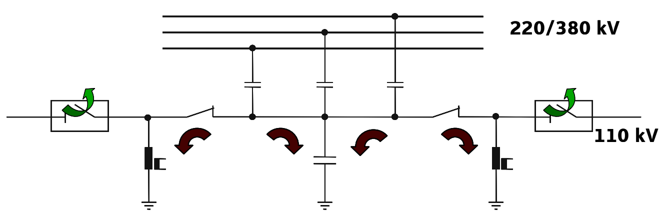

Fig. 3.5: System configuration generating ferro-resonance phenomena

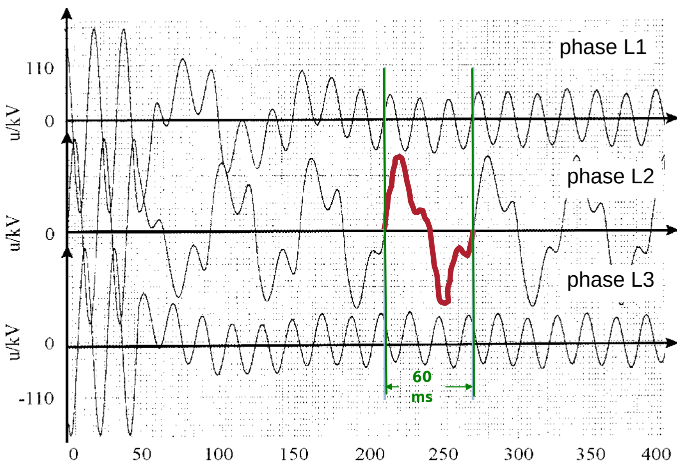

Fig. 3.6: Typical oscillogram of an oscillation caused by ferro-resonances

Fig. 3.6 shows a typical oscillogram of such an oscillation caused by ferro-resonances. In phase L2 an undamped oscillation is excited after the breaker is switched off, whereas in phase L1 the oscillation disappears after some hundred milliseconds [9].

To avoid ferro-resonance phenomena the basic design of the voltage transformers at the line entrance has to be modified. Different remedial measures were studied. However, the only one which provide sufficient damping for this case is to fit the core with a small air gap. This modification is very efficient and produces little additional costs, only. It is also suited for damping of ferro-resonance phenomena occurring in other configurations described in [8].

4. *Service experience with GIS and consequences for monitoring, testing, lifetime assessment and design improvements*

GIS are very reliable and a lot of failures which took place at previous development stages does not occur with modern equipment. Since the failure rates and the main failure causes of the switching equipment do not essentially differ from that of conventional equipment [9], in this chapter the main focus is paid to dielectric failures. Most of the data presented were collected by the German GIS User Forum – a group of GIS users in Germany and Austria [11]. The failure events were evaluated regarding the main causes of failures, the origin of failures and detectability of failures by a suitable diagnosis (Fig. 4.1…4.3).

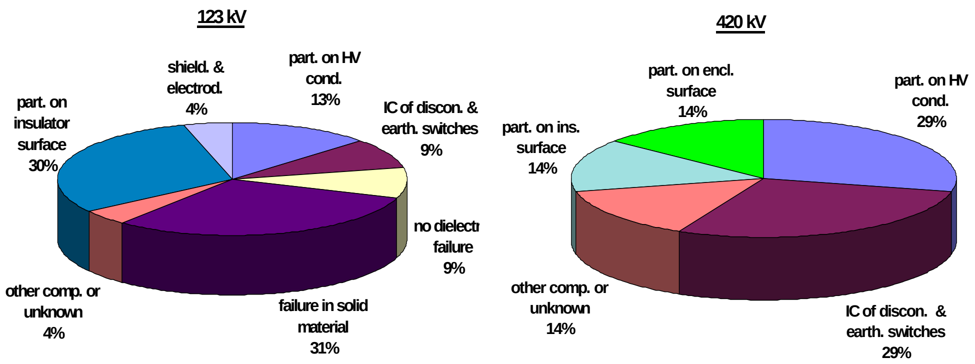

Fig. 4.1: Cause of dielectric failures in 123 kV and 420 kV GIS

The majority of failures were caused by particles, either free moving, fixed on the HV conductor or on the insulator surface. A further failure cause was due to deficiencies in insulation co-ordination of disconnectors and earthing switches during switching processes. This failure cause was more dominant in 420 kV, did also exist in 123 kV, but less remarkable. Insufficient long-term strength of solid insulation, in particular of cast resin insulated current and voltage transformers was found in 123 kV only, since in 420 kV SF6 insulated current transformers and SF6 plastic film impregnated voltage transformer are applied since the very first beginning.

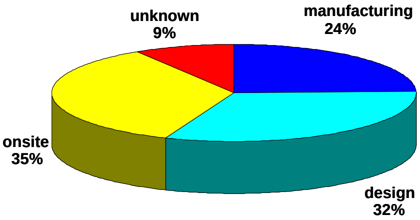

Fig. 4.2: Origin of dielectric failures in GIS

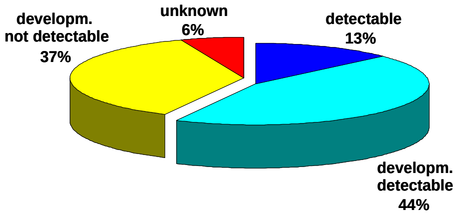

Fig. 4.3: Detectability of dielectric failures in GIS by diagnostic methods

With regard to origin of failures (Fig. 4.2) one third can be traced back to insufficient design and 25 % to deficiencies during manufacturing or assembling and one third to commissioning onsite. Design failures can be avoided by adequate type testing. As an example, since the type tests ensuring the switching capability of disconnectors and earthing switches were introduced, no failure due to deficiencies in insulation co-ordination of disconnectors and earthing switches during switching processes has become known in Germany. Failures due to deficiencies during manufacturing or assembling are meanwhile prevented by a distinctly improved manufacturing and quality assurance process. Failures due to insufficient commissioning onsite have been essentially reduced by a better qualified testing after erection on site, e. g. by additional PD testing.

As to be seen from Fig. 4.3 60 up to 70 % of the failures could have been detected by adequate monitoring and diagnostic. The defects would have been detectable partly during their development partly directly after occurrence. In any case the failures could have been avoided, a sufficient measuring sensitivity presumed. Here significant progress could be achieved by development of the UHF PD measuring technique in the recent decade. Therefore insulation monitoring of GIS seems to be reasonable [12]. But the application of permanent monitoring devices can only be justified in case of substations with high importance, in particular from the economical point of view [13]. Normally periodical measurements which can be performed by the use of mobile measuring devices should be sufficient.

From the analysis above one can conclude that the GIS design of today will be more reliable. Many irregularities, as e.g. design deficiencies or deficiencies in the manufacturing process, undue onsite testing or insufficient long-term performance of solid insulation can most probably be excluded today. Most of the incipient faults may be detected by a sufficiently sensitive onsite insulation monitoring and diagnostic technique which is available today [14].

The long-term performance of GIS of the previous development stages can be taken from Fig. 4.4. It shows the failure frequency of dielectric failures (number of failures per 100 bays) depending on the age of the stations. The service period considered amounts up to 33 years of. A distinct accumulation of dielectric failures can be recognised at the beginning of the service life and the period between 11 and 18 years of service. The first is due to the “teething“ faults. The second accumulation is mainly caused by failures in the solid insulation, primarily cast epoxy resin instrument transformers, but occasionally also tracking on insulators. After that period the failure rate remains on a low level. However, after a service time of 30 years and more an increase can be stated which might be a sign of certain aging phenomena. Additional investigations of the failure developing mechanism should allow to determine how far the failures could be avoided by preventive measures and precautionary exchange of faulty components. In any case it has to be clarified, if these failures are an indication that the equipment is reaching its end of service life.

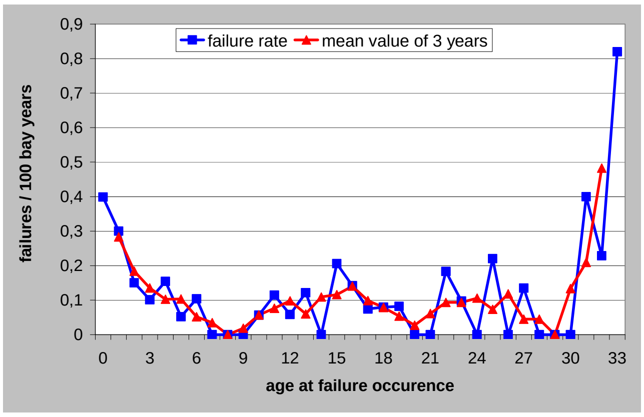

Fig. 4.4: Failure frequency of dielectric failures at a certain age of the station

5. *Conclusion*

The analysis of service experience can be used as a basis for optimization of maintenance procedures and methods, for lifetime assessment, for development of monitoring and diagnostic technique and for design improvements. With regard to HV CBs the results demonstrate that a modification of current maintenance strategy cannot be recommended for all breaker types. Puffer breakers of the first generation will reach their end of end of service life in 10 up to 15 years. However, one has to count with additional expenditures for maintenance and repair, if a high degree of reliability shall be sustained. Moreover, the 2nd generation of puffer CBs has shown an increased number of "teething" problems. The failure behaviour of self-blast breakers has changed compared to that of puffer breakers. Whereas at the later ones failures in the drive system were dominant, self-blast breakers are more affected by failures in the functional control and insulation. These major sources of failures can be identified with simple and effective methods like visual inspections or SF6 density monitoring.

The service experience on instrument transformers has shown that improvements in the fundamental equipment design and system layout are necessary. In consequence the voltage transformers are designed in a way that provides sufficient damping of ferro-resonance phenomena. Furthermore, the protection of instrument transformers in case of steep front overvoltages is improved by installation of arresters at the line entrance of the feeder.

The analysis of service experience with GIS points out that a lot of failures occurred in the past will not happen with the new GIS generation due to improvements in the basic design, manufacturing and assembling as well as testing. A lot of failures could have been detected by diagnostics, a sufficient measuring sensitivity presumed. Therefore insulation monitoring at least by periodic measurements seems to be reasonable. At older GIS an increased failure rate can be stated after a service time of 30 years and more which might be a sign of certain aging phenomena. Additional investigations of the failure developing mechanism should allow to determine how far the failures could be avoided by preventive measures and to clarify if these failures are an indication that the equipment is reaching its end of service life.

BIBLIOGRAPHY

[1] G. Balzer, D. Drescher, F. Heil, P. Kirchesch, R. Meister, C. Neumann: Evaluation of failure data of HV circuit breakers for condition based maintenance. CIGRE A3-305, 2004.

[2] CIGRE Technical Brochure No 83, "Final report of the second international enquiry on high voltage circuit-breaker failures and defects in service", 1994.

[3] B. Rusek, G. Balzer, M. Holstein, M.-S. Claessens: Possibilities for improvements of HV circuit breaker monitoring (in German). ETG-Report 104: Diagnostic of electrical equipment, 19.-20. Sept. 2006, Kassel, pp. 197-202.

[4] B. Rusek: Digital Modeling and Simulations of High Voltage Circuit Breaker Failures for Optimization of Sensor Technique. Thesis Technical University of Darmstadt, 2007.

[5] C. Neumann, N. Lambrecht: Automated, user instructed and data based inspection and diagnosis of circuit breakers (in German). ETG-Report 97: Diagnostic of electrical equipment. Cologne 2004, pp. 385-390.

[6] C. Neumann, G. Balzer, M. Hudasch, K. Liebscher, A. Strnad, K. H. Weck, T. Weinmann: Insulation co-ordination practice of German utilities - Procedures, experience and future trends. Cigre 33-102, 1998.

[7] V. Hinrichsen, R. Göhler, H. Lipken W. Breilmann: Economical overvoltage protection by metaloxide surge arresters integrated in HV AIS disconnectors – Substation integration, design and test experience. Cigre 33-104, 2000.

[8] H. Bräunlich, H. Däumling, M. Hofstetter, U. Prucker, J. Schmid, R. Minkner, H.-W. Schlierf: Ferro-resonances in MV and HV systems. Part 1: Definitions and general explanations (in German). Bulletin SEV/AES 23/2006, pp. 17-22.

[9] H. Bräunlich, H. Däumling, M. Hofstetter, U. Prucker, J. Schmid, R. Minkner, H.-W. Schlierf: Ferro-resonances in MV and HV systems. Part 2: Examples (in German). Bulletin SEV/AES 25/2006, pp. 27-30.

[10] CIGRE WG 23-10: Report on the second international survey on high voltage gasinsulated substations (GIS) service experience. CIGRE 23-102, 1998.

[11] G. Balzer, C. Neumann, A. Strnad: German utilities' experience with the service performance of GIS. SEE Conference MatPost 99:"HV & MV Substation Equipment", From their performance to the network performance. Lyon, Nov. 1999.

[12] C. Neumann; B. Krampe, R. Feger, K. Feser, M. Knapp, A. Breuer, V. Rees: PD measurements on GIS of different designs by non-conventional UHF sensors. CIGRE 15-305, 2000.

[13] Kuschel, Laskowski: Economic aspects of online monitoring of gas-insulated high voltage switchgear systems based on life cycle cost analysis. 14th ISH, China, 2005, Report G-082.

[14] CIGRE JTF 15/33.03.05: Partial discharge detection for GIS: Sensitivity verification for the UHF method and the acoustic method. ELEC-TRA No. 183, April 1999, pp. 75-87.