High-voltage Tests and Measurements during the Life Cycle of GIS

Presented originally at
HIGHVOLT Kolloquium '07
Dresden/Germany, May 14 – 15, 2007

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Abstract: This report describes the different high-voltage tests and measurements during the life cycle of GIS and the related impact to the dielectric failure rate in service. Intensive development tests, routine tests and commissioning tests are the basics for a reliable design and proven product quality. Insulation monitoring in service may help to avoid unforeseen breakdowns.

INTRODUCTION

GIS have been in service for more than 40 years and they have shown a high level of reliability with extremely small failure rates even for modern GIS showing a high compactness (**Figure 1**). This is the result of quality assurance during development, production, installation and commissioning as well as during service. Quality assurance consists of different tests and measurements during the life cycle of GIS which give feedback to the manufacturer and user (**Table 1**). All return of experience should be taken into account for the continuous improvement of the product quality.

Figure 1: Compact design of 145 kV GIS

Development tests outside of the scope of the standards, the routine tests at the manufacturers' works and the tests after installation are the most important measures to ensure a GIS life-time with high reliability and availability. Maintenance measures according manufacturer instructions ensures the performance of the equipment.
Insulation monitoring in service by PD measurement gives information, which should avoid breakdowns and shall be helpful for the asset management. The results can be used for the determination of the further operation or the equipments end of life-time. The benefits of PD monitoring are nowadays still under discussion.

Life Cycle Period	Tests and Measurements	Information for …
Research & Development	Development tests Type tests	Design
Production	Routine tests	R & D Product Quality Commissioning
Installation & Commissioning	Tests after installation (on-site tests)	R & D Production Service
Service	Maintenance Tests after extension/repair Monitoring (continuous, periodic, spontanuous)	R & D Production Installation & Commissioning Asset management Further operation End of life-time
Disposal, Recycling	Inspection Material tests	R & D

Table 1: Tests and measurements at different life cycle periods of GIS

DEVELOPMENT AND TYPE TESTS

Because the GIS technique is a well established technique nowadays, the relevant subjects concerning service stress and reliability are covered by standardized tests. Several generations of GIS have been developed since the last 40 years. Service experience from all generations provides feedback to the development departments of all manufacturers and in parallel the standardization follows by covering all open topics. The equipment related international standard for GIS is IEC 62271-203 (before last revision the numbering was IEC 60517) [1]. Beside the standardized tests which are required for each new type of GIS it is on behalf of the manufacturer to ensure the reliability by additional measures. Quality-control in the factories as well as development tests outside of the scope of the standards are the additional measures to ensure a service life of the GIS without any problems.

Type tests

Concerning the insulating capability the standard prescribes the high-voltage test requirements concerning the dielectric test values as well as the way of testing of all relevant insulations. Following the considerations of the insulation co-ordination the three main parts of insulation has to be covered: Insulation to ground and between phases and longitudinal insulation.

For each the overvoltages in services are classified in temporary and transient overvoltages. All these overvoltages are covered by the standardized test voltages: Power-frequency voltage, switching and lightning impulse voltage and the combinations of them for the special applications longitudinal insulation and between phases. The very fast transient overvoltages are not covered by a standard wave shape but with a special test arrangement simulating the overvoltage behavior in service during disconnector switching.

During type test all the required withstand voltages have to be applied to the test object for to reach the well defined acceptance criteria. As final check of the insulation properties a partial discharge measurement has to be carried out (**Figure 2**). Main purpose of this test after all other dielectric tests is to show the integrity of the insulation, mainly the solid insulation.

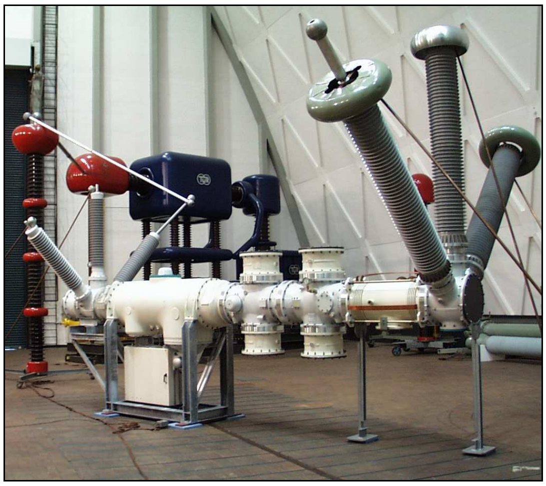

Figure 2: Final PD measurements after dielectric type test of a 145 kV GIS bay

Before starting into the type tests of new GIS some development tests were carried out to check the limits of the insulation. Safety margins can be evaluated and possibilities for improvements become obvious. Generally these tests were carried out with the same test procedures and voltages as required for the type test.

In former times a lot of development tests were necessary to reach the desired insulation requirements. Nowadays the necessity for this is low and can sometimes even been omitted due to the long experience with the GIS technique and of course due to the possibility to predict the dielectric strength by calculation of the electrical fields. The calculations of two and three dimensional geometries combined with the experience from tests of the last decades show very well the limits of the dielectric strength.

Development tests of solid insulation

The insulation to ground is the base for all test requirements, since this is the main insulation which has to be withstood the service stress during the whole life-time. In this respect the solid insulation is of major concern since the short duration power frequency and impulse withstand tests cannot ensure all aspects of high quality insulators. Within the last decades a strong increase in compactness (**Figure 1**) leaded to a higher exploitation of the electrical field and therefore to higher electrical stresses in insulating solids. Therefore basic development tests were carried out concerning the long term behavior of solid insulation.

Insulating solids can show ageing effects under high electrical stresses [2]. Ageing processes cannot be avoided and any material is subject of ageing. For this reason, the acceptable electrical field strength in the bulk of insulators has to be selected properly. Until today the relations between life-time behaviors, electrical field strength, material volume and different production processes are not completely understood nor calculable in a reliable way, but can be determined empirical.

Three dimensional field calculations (**Figure 3**) allow a highly complex and field optimized design. For optimization processes in the design basic data as acceptable electrical field strengths are necessary. Therefore long-term tests on full-size insulators or comparable test specimens have been performed with test durations of several thousand hours, resulting in reliability data concerning materials and manufacturing processes.

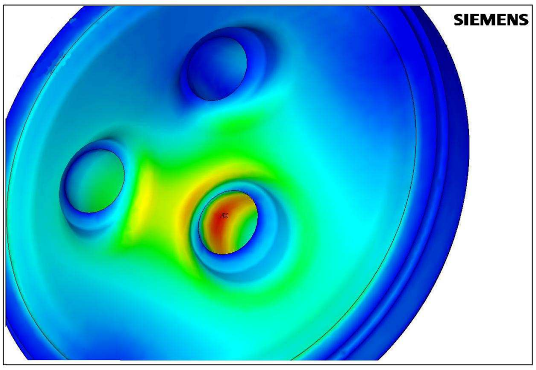

Figure 3: Example of 3D field calculation result (disk insulator for 3-phase 145 kV GIS)

Long term test procedure

All long-term tests as part of basic development tests have been performed with power-frequency voltage (50 Hz), according to the continuous high stress in service. To reach an acceleration effect of life-time the test voltages were increased up to two to five times the service stress. A large number of simultaneously tested insulators were arranged in test vessels in SF_6 atmosphere, as e.g. shown in **Figure 4**.

To obtain a reliable assessment of manufacturing processes, all tests on epoxy insulators have been performed on real size insulators. With this method an uncertainty of extrapolation from small test samples to real size insulators can be excluded.

Figure 4: Example of test setup for disk insulators

Different insulating components as post and disk insulators made of different types of mineralic filled epoxies as well as operating rod and support insulator samples made of fiber-reinforced epoxies have been tested.

The long term tests are performed with a statistical significant number of insulators of the same type, e.g. 20 test samples. All intended test insulators run through a high voltage routine test in combination with high-sensitive PD measurements before the long-term test. This common quality control procedure eliminates potential early failures during long term tests.

The long-term test voltage is increased two to five times in relation to the service-voltage stress. Therefore an acceleration effect of life-time is possible. The applied electrical field strengths are high enough for a time-lapse-effect, but they are low enough to avoid unrealistic ageing processes. The test voltage is applied until one of the test specimens fails. After the faulty insulator has been removed, the test is continued with all remaining test specimens at the same voltage. This procedure is repeated until several thousand hours have been reached.

Statistical evaluation

The test results are evaluated statistically in order to determine predictions of insulator's life-time behavior (voltage endurance graphs). The mathematical principle is based on a Weibull distribution [3].

The physical phenomena can be described with the well-known bath-tub curve (**Figure 5**) [2].

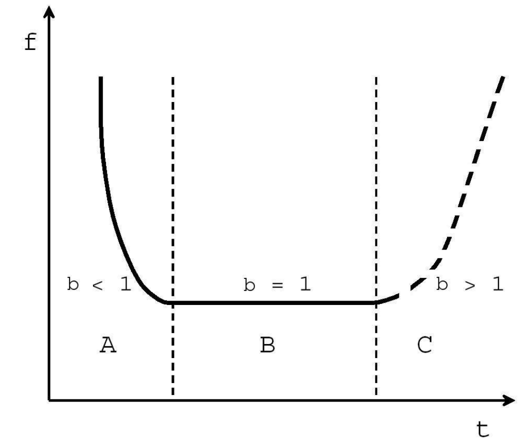

Figure 5: Bath tub curve (failure rate versus time)
A: teething failures
B: random failures
C: ageing failures

For the evaluation of tests the failures in the beginning of the time scale (A) have been excluded by routine tests as part of the production process. They are commonly named “teething faults”. Part B of the curve describes the predominant behavior of GIS in service and is therefore the relevant section for long-term investigations. The end of service life (rising branch C) has not been observed for GIS insulators in service despite the meanwhile long time of approx. 40 years for the first GIS. Also no indication of a rising branch was found during long-term tests.

With a constant failure rate in part B (exponent of Weibull function is b=1) the function of the failure probability *F* (*t*) is an exponential function. In **Figure 6** an example of the evaluation of a test result is presented. The cumulative failure frequency *H*(*t*) describes the portion of failed insulators within the total number of tested insulators versus time. The failure probability *F*(*t*) is an approximation of the cumulative failure frequency *H*(*t*). *F*(*t*) shows an exponential behavior. This means, that the failure rate is constant.

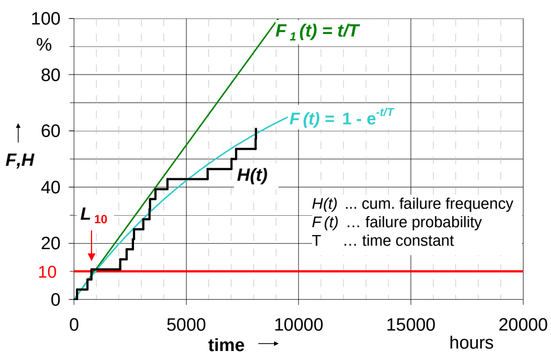

Figure 6: Evaluation and description of test results

The exponential function *F*(*t*) and the linear function F_1 (*t*) are approximately equal for failure probabilities in the range 0 - 10 %. Therefore the exponential function can be approximated by a linear function of time through the origin for the mentioned range, which is the range of interest for the long term investigations. The time to breakdown for 10 % failure probability L_{10} can be determined easily. All following life-time estimations are based on these approximated L_{10}-values.

Voltage endurance graphs (life-time curves) describe the relation of the electrical field strength *E* in relation to time with the failure probability as parameter and are usually drawn with logarithmic scales.
Voltage endurance graphs are approximated with a large number of test results. The graphs can be described with the “inverse power law“ equation

$$L_{10} = L_{10(0)} * \left(\frac{E}{E_0} \right)^{-n} \qquad (1)$$

with the voltage endurance coefficient *n* .

For the high reliability of GIS extremely low levels of failure probabilities are required. E.g. a failure probability of 0,01 % after 50 years is aimed. This means, that one of 10.000 insulators could fail within a service life of 50 years [4].

Test results

Several different types of insulators have been investigated within the last years. The test durations in the long-term tests ranged from 1.000 up to 15.000 hours. The test results confirmed the validity of the inverse power law (Equation 1) for the investigated materials and test methods. Nearly all test results followed a linear dependence on the logarithmic time scale within a relative small scatter.

Figure 7 shows the voltage endurance graph for several types of cast epoxy insulators. The solid lines represent the life-time curves for 10 % failure probability, the dotted lines are the extrapolated 0,01 % failure probability.

By means of these voltage endurance graphs maximum electrical field strength for insulator designs have been defined. One parameter for the acceptable maximum service stress is the insulator’s volume. For small post insulators as well as disk insulators with a medium volume the acceptable stress is remarkable higher than for disks with a large volume (service stress for large volumes is not indicated in **Figure 7**).

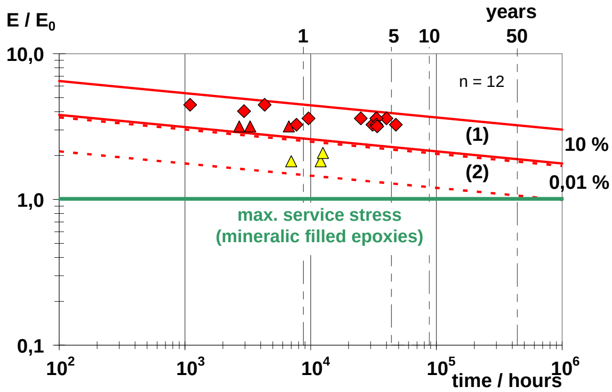

Figure 7: Voltage-endurance graph of epoxy insulators (E_0 = maximum service stress)

(1): band for 10 % failure probability
(2): band for 0,01 % failure probability
red: small and medium volume
yellow: large volume (with lower service stress, not indicated here)

ROUTINE TEST

The quality of production is checked by routine tests on complete bays or transport units at the manufacturer's works. The dielectric routine test consists of a power frequency voltage test on the main circuit including PD measurement according to the IEC standard [1]. The PD level needs to be lower than 5 pC. A noise level lower than 2 pC is necessary to ensure this requirement. Such a sensitivity can only be reached by shielded high voltage test equipment and HF filtering of the mains. For solid insulators a high voltage routine test with high-sensitive PD measurements gives benefits for the assembly at the production.

During routine test the UHF PD detection method is applied in parallel to the conventional PD measurement. Nowadays the quality assurance for the equipment under test is performed mainly by a high-sensitive UHF PD detection. For GIS with installed UHF PD couplers these measurements can be used as a reference for the on-site HV test.

ON-SITE TEST AFTER INSTALLATION

While routine testing in the factory ensures that the quality of the transport units is in accordance with the components which passed the type tests, the on-site test should check the dielectric integrity of the completed installation. The on-site test must be able to eliminate different types of defects which might give rise to an internal fault in service:

- incorrect assembly
- presence of foreign bodies or other contaminants such as free metallic particles and protrusions
- damage during transport, storage or installation

Different test procedures for on-site testing of GIS are recommended by IEC 62271-203 [1]. For GIS with rated voltage levels of $U_m \leq 170$ kV the application of power-frequency voltage is recommended for on-site testing (procedure A). A frequency range of 10 - 300 Hz should be used for the power-frequency voltage test. GIS with rated voltages of $U_m \geq 245$ kV should be tested either with power frequency voltage combined with PD measurement (procedure B) or as an alternative with a power frequency voltage test followed by a lightning impulse test (procedure C). However, due to practical and economical interests, deviations of the recommended test procedures and parameters are expressly allowed by IEC. GIS manufacturer and users must agree on an appropriate test procedure. For typical GIS with rated voltage levels up to $U_m = 245$ kV the HV test procedure A is sufficient to ensure the dielectric integrity.

On-site AC testing of GIS can be combined with sensitive PD measurements in order to detect small defects [5]. Different methods can be used for on-site PD measurements: Conventional PD measurement according IEC 60270, UHF method as well as the acoustic PD detection method. The Cigré proposal for on-site testing of GIS recommends a highest permissible PD level of 5 pC or equivalent. LI tests are of practical relevance in case the PD detection sensitivity is not sufficient due to external noise.

Extensive investigations have confirmed that the detection of PD using the UHF method results in higher or at least the same sensitivity as detection by PD measurement as set out in IEC 60270. UHF PD detection does, however, not provide a direct correlation with the standardised "pC-values" according to IEC 60270. Cigré has therefore developed a procedure verifying that it is possible to detect "bouncing particles with 5 pC" in complete GIS substations. First, a laboratory test is carried out for each GIS type and for the UHF PD measuring system used, in order to establish the direct correlation between the 5 pC value of a bouncing particle and the amplitude of a voltage step generator. Afterwards on-site the voltage signal is fed in at a PD coupler and should be detected at the directly adjacent PD coupler. The signal amplitudes measured are a clear indication of the varying attenuation of the UHF signals between the PD couplers. The sensitivity verification is used to check on-site the correct positioning of the PD couplers in a GIS. Recent results of measurements showed that depending on the GIS type, bay design and the substation layout, the maximum permissible distance between two PD sensors is in the range 10 - 30 m. However, in case of long outgoing GIS feeders or

GIL the distance can be greater than 250 m due to the low attenuation of the UHF signals in these designs.

Conventional test transformers have been used from the very beginning of on-site testing of GIS. For switchgear with operating voltages above 170 kV, however, the required test transformers and control devices were found to be both large and heavy. High feeding power capacities were needed unless suitable compensation reactors were provided.
Nowadays compact, portable and lightweight frequency-tuned resonance test sets are available which enable efficient on-site AC testing of GIS (**Figure 8**).

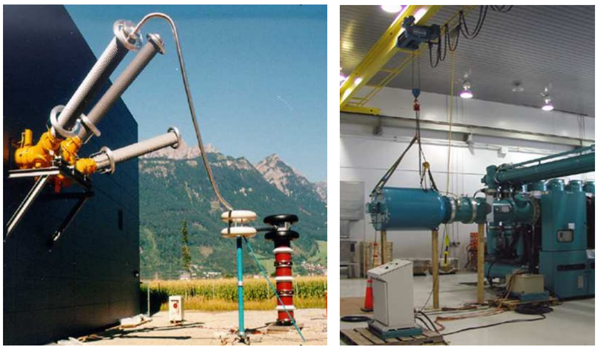

Figure 8: Examples of frequency tuned resonant test sets for on-site testing of GIS

MEASURES DURING SERVICE

Maintenance

A GIS offers a high degree of reliability, even when the limits of wear are approached. The purpose of maintenance is to:
- determine to what extent certain parts have worn and to assess their state
- ensure that parts still in perfect condition
- preventive replacement of certain parts

Standard maintenance measures like visual check and major inspection on GIS are performed after predefined time intervals or based on the number of mechanical operating cycles (wear). The gas compartments of a GIS need to be opened only once during the life-time of up to 50 years in case of a low number of switching operations. A high-voltage test is not required by the standard maintenance strategy. However, nowadays some of the major inspections are combined with insulation monitoring by PD measurement.

Monitoring

In general insulation monitoring during service aims at detection of teething and random faults and exploitation of life-time. GIS have been in service for about 40 years and they have shown a high level of reliability with extremely low failure rates. However, the return of experience shows that some of the in-service failures are related to defects in the insulation system. **Figure 9** shows the distribution for the main failure causes in GIS. A sufficient PD detection sensitivity presumed, about 25 % of the major failures could have been detected by PD monitoring. For GIS of modern design this value is estimated to about 60 % [6].

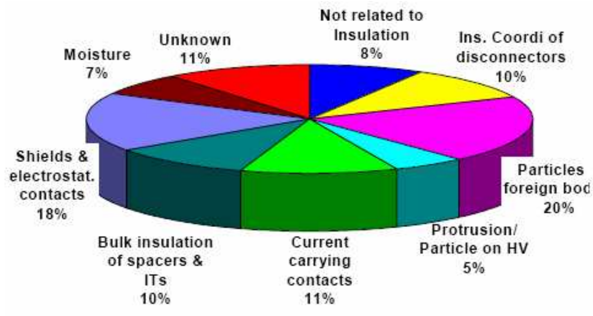

Figure 9: Causes for major failures in GIS

Nowadays PD monitoring (PDM) systems are available for continuous insulation monitoring, which based on the UHF technique (**Figure 10**). The UHF signals may readily be picked up by couplers fitted either inside the GIS chambers, or over mobile dielectric apertures in the enclosure. The UHF signals can be displayed in different ways where their characteristic patterns reveal the nature of any defect that might be present in the GIS. The captured pulse sequences are analysed automatically with good accuracy by modern PDM systems and only service relevant PD alarms are submitted to the substation control system [7]. With such an early warning of an impending breakdown, utilities can take appropriate action.

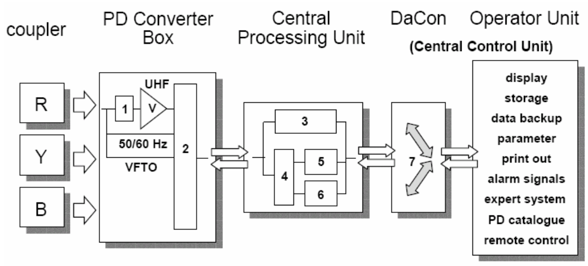

Figure 10: PDM system hardware arrangement

Modern PDM systems consist of standardized electronic boards and commercially available components with high reliability and an expected life-time of more than 15 years. Different hardware modules can be easily arranged to build up a customized PDM system which enables a sensitive PD monitoring with a detection level of about -75 dBm. The man-machine-interface for manual operation of the system is realized by user-friendly software with flexible PD data display including trend diagrams and customized reporting of the monitoring results. Worldwide remote control of the systems is state-of-the-art.

The benefit of PDM system application can be described by the successful detection of PD defects during GIS service and the prevention of related breakdowns. A lot of information is available nowadays for the statistical evaluation of PDM systems [7]. For one type of PDM system PD data are continuously taken from 363 UHF couplers, which are located at six GIS with rated voltages from 245 kV to 550 kV. The PD detection sensitivity is equivalent to an apparent charge of 5 pC and often much better. PD data of a seven years period and 223 bay-years are available in total.

Only one defect was found in service. A floating electrode defect was detected by the PDM system and confirmed by visual inspection during the repair work. For all GIS with PDM system application no in-service breakdown has occurred so far. The PD defect rate for the available data basis can be calculated as follows:

Number of UHF couplers	363
Number of bay-years	223
Number of UHF coupler-years	1356
Total number of defects (critical PD)	1
PD defects per 100 bay-years	0.45
PD defects per 100 UHF coupler-years	0.074

An in-service breakdown in a GIS typically takes more than a week to repair, and the costs of this, together with the consequent circuit disruption and loss of supply in a single outage, usually far outweigh the initial cost of high-performance PDM systems.

A detailed life-cycle-cost calculation based on typical or type-related failure rates and outage costs for GIS substations can confirm the above mentioned general statement about application of continuous PDM systems [8].

An insulation monitoring can also be obtained by periodic checks, because some of the failures do not occur spontaneously. The periodic PD measurement can be realized by suitable mobile acoustic or UHF PD instruments. Very often the first PD measurement is done at the on-site HV test after installation. The time interval for the next measurement should be based on experience or can be linked to the GIS warranty period. Most of the critical defects can also be detected by acoustic PD instruments and this method becomes more important in future due to the evaluation of the insulation system of the installed GIS base where UHF couplers can not be applied.

Risk Assessment

Risk assessment on defects in GIS based on PD diagnosis is a complex task, which is influenced by technical and other impact parameters. The approach of CIGRÉ TF D1.03.09 to design a risk assessment system is to combine the defect related breakdown probability with the consequences (outcome of a failure: e.g. costs, safety and social-economic implications) [9]. Such a risk assessment system can be used by asset managers. An improvement of the reliability and availability of GIS can be obtained and exchange measures, if needed, may be initiated before a breakdown or an outage occurs. In this way a life exploitation of the equipment is possible and a higher utilization is accomplished leading to considerable savings of life cycle costs. However, without significant PD measurements and meaningful raw data nobody is able to perform a proper risk assessment.

The principal steps of the proposed risk assessment based on PD diagnostics are the following:

1) PD measurement which is able to detect the critical defects
2) Identification of type of defect
3) Estimation of criticality of defect
4) Risk assessment based on breakdown probability and consequences

Figure 11 shows the flowchart of the proposed risk assessment procedure.

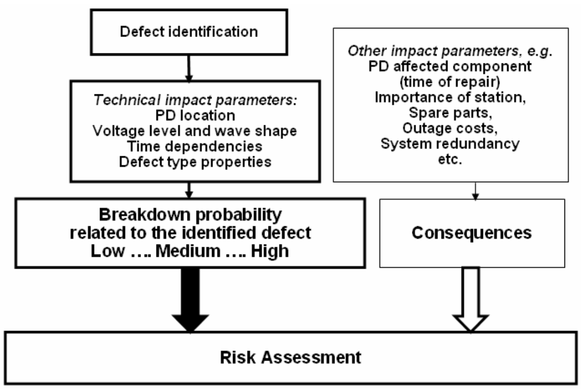

Figure 11: Flowchart of the proposed risk assessment procedure

The technical impact parameters for the different defects are well known and they can be evaluated by the PD measurement and additional information. For the calculation of the breakdown probability an equation was introduced, which take into account the evaluation of the technical aspects, the diagnosis confidence and the defect specific failure probability. The calculation of the consequences shall be done in a similar way.

The risk assessment diagram combines the calculated breakdown probability and consequences by three risk areas (**Figure 12**). A ranking for different defects is possible. **Table 2** shows the measures for each of the risk areas. Further discussion is ongoing about the calculation of the consequences and how to set the borderlines for the different risk areas.

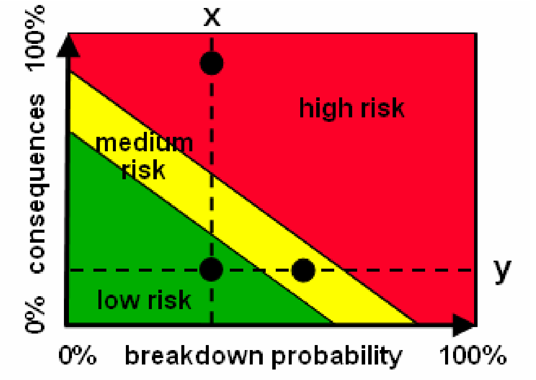

Figure 12: Risk assessment diagram for defects in GIS based on PD diagnostics

Low Risk	follow normal maintenance strategy, no further action
Medium Risk	reduce maintenance interval, observation of the defect development
High Risk	action with (human) expert intervention: - inspection of defect location and removal of smaller defects - replacement of the component in question - replacement of the complete GIS, because of reaching its end of life

Table 2: Risk level and related measures

DISCUSSION

Different tests and measurements are performed during the life cycle of GIS. A rough estimation given in **Table 3** shows the impact of the different HV tests and measurements on the dielectric failure rate of GIS in service. The development tests as well as the routine tests and commissioning tests gives the highest positive impact, because a reliable design and proven product quality are the basics for low failure rates during service. Maintenance is an important measure during the life cycle of GIS. Visual checks and inspections ensure the product quality dependent from particular service stress and wear. Type tests shows that the general GIS layout and design follows the requirements of the standards, but there is no direct link to the GIS service failure rate. The expected positive impact of continuous PD monitoring during service on the dielectric failure rate is in general not proven up to now. Most applications of PDM systems are based on experience with high type-related failure rates or life-cycle-cost calculations with high outage costs.

Development tests	+++
Type test	+
Routine test	+++
On-site test	+++
Maintenance	++
Monitoring	+

Table 3: Impact of tests and measurements on dielectric failure rate of GIS

CONCLUSIONS

Modern GIS are of very compact design. Within the last decades a strong increase in compactness leads to increased electrical stresses of the insulation. Standardized test procedures cover all kinds of possible service stress. The general layout and design details are proven by type tests and the production process is supervised by the routine tests.
Concerning the long term performance of solid insulation additional non-standardized testing is done. For this purpose long-term tests lasting more than 1.000 hours with increased voltage stressing on real-size insulators have been done. With additional modern 3D field calculations a fast and reliable design optimization is possible and life-time predictions for single insulators can be made.
The on-site test should check the dielectric integrity of the completed installation and must be able to eliminate all defects which might give rise to an internal fault in service. On-site AC testing of GIS can be combined with sensitive PD measurements in order to detect even small defects.
Insulation monitoring during service aims at detection of teething and random faults and exploitation of GIS life-time. Nowadays PDM systems are available, which based on the UHF technique. A detailed life-cycle-cost calculation based on failure rates and outage costs should confirm the benefits of continuous PDM system application.
Today's experiences with GIS in service confirm

the outstanding reliability of the insulation components, based on adequate design and quality assurance tests from the beginning of the development up to commissioning and maintenance.

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ZUSAMMENFASSUNG

Gasisolierte Schaltanlagen (GIS) sind seit mehr als 40 Jahren weltweit im Betrieb und zeichnen sich durch eine geringe Fehlerhäufigkeit sowie eine hohe Betriebssicherheit und Verfügbarkeit aus. Die kontinuierliche Verringerung der Abmessungen in den letzten Jahrzehnten führte zu einer Erhöhung der elektrischen Betriebsfeldstärken. Die korrekte Auslegung und Konstruktion einer GIS wird durch Typprüfungen nachgewiesen, wobei die im Betrieb auftretenden Beanspruchungen durch genormte Prüfverfahren nachgebildet und abgesichert werden. Die weitere Qualitätssicherung in der Fertigung erfolgt durch Stückprüfungen.
Im Hinblick auf das Langzeitverhalten von Gießharzisolatoren werden zusätzliche Entwicklungsprüfungen durchgeführt. Es erfolgen Langzeitversuche an originalen Isolatoren mit erhöhter elektrischer Beanspruchung und einer Dauer von mehr als 1.000 Stunden. Mit Hilfe von zusätzlichen 3D-Feldberechnungen ist eine Optimierung der dielektrischen Auslegung möglich. Anhand der Untersuchungen ist für die Gießharzisolatoren eine Abschätzung der Lebensdauer möglich.
Vor-Ort-Prüfungen müssen die Betriebsbereitschaft der Schaltanlage sicherstellen. Dazu sind alle betriebsrelevanten Defekte eindeutig zu ermitteln und zu beseitigen. Die Hochspannungsprüfung auf der Baustelle kann dafür mit einer empfindlichen TE-Messung ergänzt werden.
Die Überwachung des dielektrischen Anlagenzustandes im Betrieb soll Ausfälle vermeiden und eine Verlängerung der Betriebsdauer ermöglichen. Die dazu erforderlichen TE-Monitoringsysteme sind verfügbar. Der tatsächliche Vorteil dieser Überwachungssysteme ist allerdings durch eine detaillierte Berechung der Lebensdauerkosten unter Berücksichtigung von Fehlerraten und Ausfallkosten für die Gesamtanlage nachzuweisen.
Die vorliegenden Betriebserfahrungen bestätigen die hohe Qualität der gasisolierten Schaltanlagen. Die Vorraussetzung dafür ist die konsequente Qualitätssicherung durch Messungen und Prüfungen im gesamten Lebenszyklus einer GIS. Den Hochspannungsprüfungen und TE-Messungen kommt dabei eine besondere Bedeutung zu.