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2.2

On site tests of GIS

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Abstract: Due to the required reliability and long-life cycle of GIS, all quality control measures are highly important, especially the on site final acceptance test. In this paper the test and measurement techniques for on site dielectric tests of GIS are presented and a new UHF PD method is proposed. Based on the defect types and their detectability, specific combinations of tests are proposed by technical committees in order to detect all relevant defects. AC test combined with a sensitive PD measurement has become the standard procedure. The suitability of the different PD measurement techniques are discussed and different types of UHF methods are shown. To achieve optimum sensitivity, interference suppression, and simultaneous measurement at different sensors, a tuned medium-band UHF method is proposed. To further enhance testing quality, integral tests help avoid reopening of the GIS after completion, and also test the interfaces and components with higher risk of faults. Dielectric integrity measurements are increasing on older GIS, so the application of external UHF PD sensors and their specific features are discussed.

1 INTRODUCTION

Gas insulated substations (GIS) form important network nodes, particularly in densely populated urban areas. Outages at such nodes can result in blackouts of large areas and costly shutdowns of sensitive industrial processes. Therefore all quality control measures are of high importance, especially final acceptance tests. Dielectric integrity measurements following repairs or discovery of systematic faults, and at the end of the expected service life, also help to maintain reliability and eventually to extend the service life. Today the expected service life of a GIS is approx. 35 – 50 years [1, p89]. In IEC 60071-2 [2] the target failure rate recommendation for GIS insulation co-ordination is 0.1 failures per 100 bay-years. The first CIGRE report of the joint working group 33/23.12 on the return-of-failure experience covered GIS installed between 1967 and 1992; it showed a dielectric failure rate of 0.9 per 100 bay-years for all voltage levels [3]. The highest failure rate, 3.9, was found at 550 kV GIS, while the lowest failure rate of 0.26, for 125 – 145 kV GIS, is still slightly above the target value of 0.1. Five years later the second set of statistics still reported a total failure frequency of 0.75 failures per 100 bay-years [4]. Furthermore it is stated that up to 60% of the past dielectric failures could have been detected early enough with diagnostic techniques [3, p79].

All these figures show the need of effective on-site tests and diagnostic techniques in order to achieve the required high reliability and service life.

2 TYPES OF DEFECTS

Typical types of defects encountered in GIS are:

- Particle on enclosure (free moving)
- Particle on insulating material
- Protrusion on conductor
- Protrusion on enclosure
- Floating conducting part (electrode e.g.)
- Void in insulating material
- Delamination of insulation from electrode
- Cracks in insulation material

One of the most common defects are **free moving particles**, typically originating from e.g. broken threads (fixing bolts, density monitors, ...), particles from the clothes of assembly personnel, etc.. The critical length is in the range 2 ... 5 mm [3, p 91].

Particles on insulating material are particularly critical. In case of partial discharge (PD) inception, the resulting surface charges can distort the electrical field distribution on the insulator surface, which can significantly reduce the insulating capability. PD levels of critical particles on insulating material (length approx. 2 mm) are typically very low (approx. 1 pC or below).

Protrusions on conductor or enclosure are formed by protruding thread fragments, particles sticking on electrodes due to grease, parts of sheared off O-rings, etc.. Similarly to particles on insulators, they can lead to a significant reduction of the insulating capabilities at transient voltages.

Floating conducting parts such as loose electrodes or shields on the centre conductor, switching components, or moving parts like insulating shafts typically produce very high levels of PD (up to nC), yet won't cause a flashover at test voltage. Sometimes this PD can even be heard. If e.g. an electrode is not significantly displaced from its correct position or parts have fallen off due to spark erosion, no immediate danger for a breakdown exists. Nevertheless, the defect has to be removed. Also, the high PD-level prevents detection of other defects with lower amplitude. In addition, if the electrical field leaks out of GIS (e.g. at spacers with no metallic flange or at large inspection windows) with sufficient strength, particles on the outside of the GIS also can generate floating type PD.

Voids in insulating material generally form during the casting process of the insulator. Voids of 1 mm and below can generate PD, due to the local electric field enhancement and the gas (often at low pressure) inside them [5,6]. Constant PD, even at low level and acting over years or tens of years, can lead to treeing and finally to a breakdown.

For on-site commissioning tests of new GIS above 50 kV service voltage, voids are of low importance, since large and medium size voids are detected in the routine tests with sensitive PD measurement. Small voids which don't generate PD during the 1 Minute test due to statistical time lag can be triggered with x-ray induced discharge initiation and then rejected [5, 7]. An acceptance limit of 1 pC is reported in literature by a Japanese manufacturer [6].

New GIS of 50 kV service voltage and below are often equipped with cast resin voltage transformers. A problem arises owing to differing acceptance criteria for PD-levels. For similar voltage levels, the GIS may have an acceptance level of 20 pC, while the voltage transformer acceptance level is 50 pC. If PD signals are detected during an on-site test of the entire GIS, the situation can get complex.

Voids can become significant in the case of older GIS since PD measurements were insufficiently sensitive or were never done. An in-service measurement may reveal an insulator weakened by treeing which can then be replaced.

Delamination and cracks in insulating material can occur due to strong mechanical impact or stress, incorrect assembly, too-high tolerances, shrinkage during curing, etc. Similarly to voids, this type of defect can also lead to treeing and eventual breakdown [6].

3 TEST PROCEDURES ON SITE

GIS typically consists of modular components which undergo thorough factory testing and are then assembled to form a complete installation on site. Experience has shown the risk of mechanical damage due to transport, incorrect assembly, or inadvertently inserting particles or other foreign objects into the GIS. Particles hidden in threads or gaps can find their way to critical locations inside the GIS due to vibration during transport. Thus even after a successful factory test, the dielectric strength can be reduced. According to IEC 62271-203 (2003) [8], the entire GIS should be tested including all components and assembly units.

In the factory the assembly units are exposed to a 1 minute AC voltage withstand test followed by a PD measurement (without specification of the duration of the exposure). The criteria is a PD-level of < 5 pC (depending on the standards < 10 pC for individual components).

Each newly installed part of a GIS should be tested on site. Three different procedures are proposed:

- Procedure A: AC test only (recommended for service voltage levels ≤ 170 kV)
- Procedure B: AC test combined with PD measurement (recommended for service voltage levels ≥ 245 kV)
- Procedure C : AC test combined with lightning impulse test (alternative to B)

These are the minimum requirements according to the standards. Today it is common to carry out PD measurements at lower voltages than mentioned above.

Some typical on-site test setups are now shown.

Figure 1 shows an AC resonant test set connected to the busbar of a 3-phase encapsulated 123-kV-GIS. In detail: reactors (1) with 162H, voltage divider with additional capacitive load (2) 6nF in total and test bushing (3) with phase selector (4). The test voltage was 200 kV.

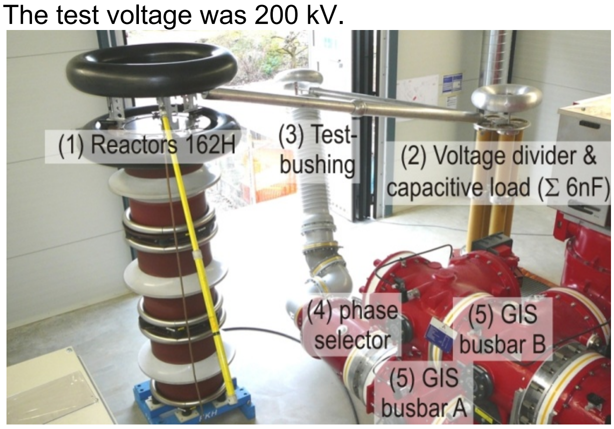

Fig. 1: AC resonant test set connected to a 123-kV-GIS

Figure 2 shows an encapsulated AC resonant test set connected at the busbar (4) of a 3-phase encapsulated 123-kV GIS. In detail: exciter transformer (1), reactor (2) with 720H, phase selector (3).

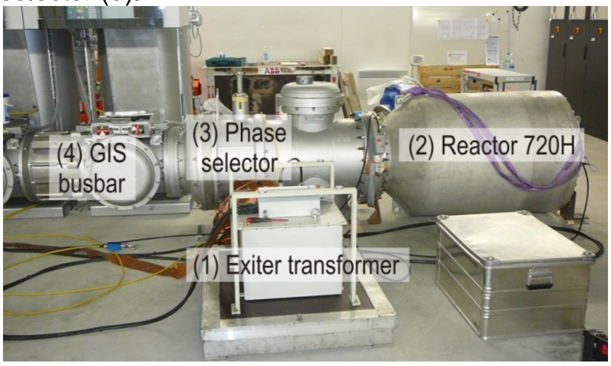

Fig. 2: Encapsulated AC resonant test set connected to a 123-kV-GIS

Figure 3 shows a measurement setup for a tuned narrowband UHF-PD-measurement including time of flight measurement for PD localisation. For high sensitivity, a preamplifier with approx. 50 dB gain is attached directly to the PD-sensor (inset).

Fig. 3: PD-Measurement setup for tuned narrowband UHF-PD-measurement including time of flight measurement for PD localisation. Lower right: preamplifier attached directly to the PD sensor.

Figure 4 shows a test setup for an oscillating lightning impulse test (OLI) at a 400 kV substation. In detail: charging unit (1), capacitor bank with spark gaps (2), inductances (3) voltage divider (4).

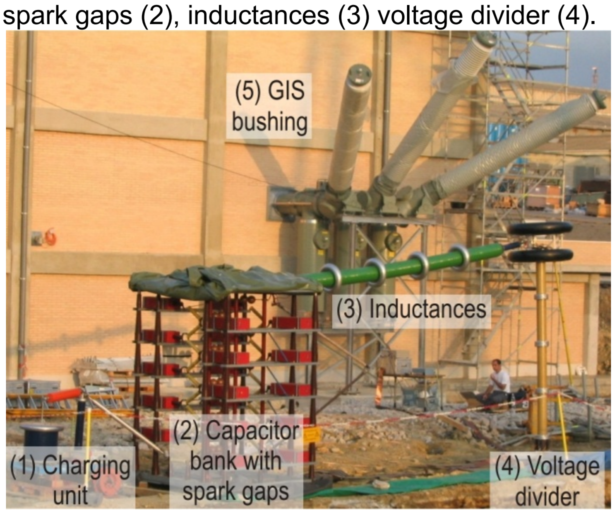

Fig. 4: Test set up for oscillating lightning impulse test at a 400-kV-GIS.

The relative effectiveness of on-site tests on GIS defects has been reported by the CIGRE JWG 33/23.12 [3, p87]. It is not possible to detect all critical defects using AC test voltage only. For example, sharp protrusions or particles on spacers are not effectively detected due to corona stabilisation [3, 9]; these defects are revealed with lightning impulse (LI) tests. However, LI tests do not effectively detect free particles (the most common defect) or floating parts.
Two combinations of test techniques are proposed to achieve the most effective on-site tests: AC test combined with LI test and AC test combined with a sensitive PD measurement at 80% of the 1 minute AC test level [3]. The AC test should be conducted with “high AC” test voltage. This means at an rms value equal to the highest value of the pair 0.36 x lightning impulse withstand level and 0.8 x AC withstand level.
The recommended and most frequently applied procedure is an AC test with a sensitive PD measurement. However often in practice, the lower voltage level for the PD measurement proposed by the IEC standard is applied instead of the higher voltage level recommended by the CIGRE JWG 33/23.12.

4 PD MEASUREMENT TECHNIQUES

Since there is no correlation between the PD level detected (regardless of method used) and the flashover voltage of the defects (e.g. particle on insulating material / floating electrode) the PD measurement must be as sensitive as possible.
In order to be of any use, the PD-signal has to be extensively characterized:

- The sensitivity of the PD-measurement has to be optimized in order to get a clear fingerprint the PD source (a phase-resolved PD-pattern).
- Based on the fingerprint, the type of defect is determined (e.g. a floating part). This step is often not easy and more information is required.
- In general it must be assured that the measured PD-signal is not coming from an external source; e.g. a floating part in the area of the AC test setup
- In order to prove whether the PD will be active at service voltage level, the inception and extinction voltage are determined.
- The temporal behaviour of the signal is determined (continuous, intermittent, extinction after a certain time, etc.).
- Finally the PD source has to the localized by dividing up the GIS or using acoustic measurements or time of flight (TOF) techniques.

Following this process and considering the specific GIS design, an evaluation can be made and actions taken. In newly installed GIS the PD source is generally removed. In the case of older GIS, additional factors may be considered such as estimating the risk of a breakdown, importance of the substation, the possibility for shut down and repair, etc.

PD measurement techniques for on-site test can be subdivided as follows::

- Conventional (IEC 60270); 30 kHz ... 1 MHz
- UHF 0.1 ... 2 GHz (3m .. 0.15m Wavelength)
- Acoustic 10 KHz ... > 100 kHz

Under optimal conditions all 3 methods can achieve a sensitivity of < 1 pC. This depends on the level and frequency of interference signals, the type of defect, the signal path between defect and sensing device, and characteristics of the latter.
The sensitivity of the **conventional method** depends strongly on the level and frequency of interference signals, i.e. electrical shielding of the test and measurement setup. An industrial environment with frequency converters, a substation with air insulated equipment or a generator in a power plant are examples of highly problematic interference environments. Normally this method is only applied when the entire test setup is encapsulated, in which case both high sensitivity and calibration are possible.
Following the test, the encapsulated test setup must be removed, thus necessitating opening of the GIS and leading to the danger of introducing particles. Removal the PD-coupler means it is not available for future measurements in service. Furthermore, localisation of PD can only be done acoustically since TOF measurements require much higher bandwidth (1 GHz or more).
The **UHF-Method** is much more resistant to interference signals; especially with the variable narrow-band method it is possible to select frequency windows free of interference. For the most common defect (moving particle) a high sensitivity is achieved. While it is not possible to calibrate this method due to the underlying physics, CIGRE details a sensitivity check which verifies the number of UHF-PD-sensor in a GIS necessary to achieve a minimum sensitivity of 5 pC for a certain type of defect [10]. Details of the implementation of the sensitivity check are discussed in the CIGRE WG D1.25.
The sensitivity is defect dependent. Figure 5 shows the ratio of radiated radio frequency (RF) energy and the PD-level of a defect measured with the conventional method (IEC 60270) for different defect types [11].

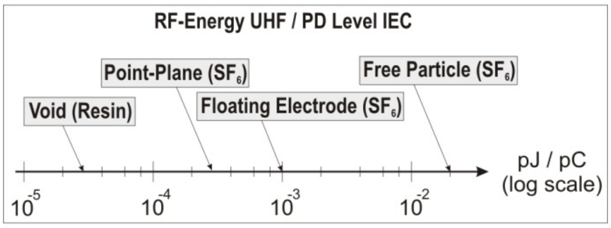

Fig. 5: Ratio of RF energy and PD level with conventional method (IEC) for different defect types [11].

This gives a rough impression of the radiated RF-energy depending on the defect type. Since the measurements were made in the near field of the signal emitter only slight changes in the antenna position can lead to significant changes in the measured amplitude. Also the volume and geometry of the test chamber has a significant influence on the result.
For the **acoustic method** the sensitivity strongly depends on the material properties in the signal path between PD source and sensor. Typically PD-signals can be measured only within a range of 1 ... 2 m. This method is therefore seldom used as a criteria for commissioning tests due to the high number of measurement points required. However, the method is well suited for the localization of certain defects like moving particles.

For on-site commissioning testing of GIS, the **UHF-Method** has established itself as the standard method for PD measurement.
The extremely short rise times of PD signals in GIS result in frequency spectra extending to very high frequencies. Rise times from PD signals of protrusions down to 35 psec, corresponding to frequencies up to 10 GHz, have been verified [12]. Signals at such high frequencies are radiated and picked up with antennas; purpose-built broadband UHF sensors are designed and built into GIS to couple out the PD signals.
The wavelengths of the PD signals are of the same order as the physical dimensions of the GIS, while the nominally coaxial signal path of the GIS exhibits many discontinuities which lead to complex resonance patterns of electromagnetic waves within each compartment. Thus the magnitude of the detected signals depends strongly on the location and also to some degree on the orientation of the defect relative to the coupler [10 p77]. For practical reasons a calibration of the UHF-method is therefore not possible. Due to the skin effect and losses at spacers the propagating signals are damped; these effects are frequency dependent.
It is therefore important that a sufficient number of sensors are installed to guarantee a minimum sensitivity. This can be verified in situ using the recommended CIGRE sensitivity check [10]. Typically a sensor is installed at the end section of a feeder and then at approx. every 2^{nd} or 3^{rd} bay in the busbar and at the ends of the busbar. More sensors are added in case of longer feeder extensions or after an accumulation of elbow units.
Applying the UHF-Method, the acceptance criteria required by the major Swiss utilities is “No phase correlated PD signals measurable at the voltage level of PD measurement U_{PD} (after the 1 minute AC withstand test). Decisive for the assessment is a phase correlated PD pattern with 1 minute integration time at U_{PD}”. All the GIS tested by FKH with the tuned UHF narrowband measurement technique (explained below) have passed this criteria.

Several types of UHF methods are used:

- Tuned UHF narrowband measurement with variable centre frequency
- UHF broadband measurement with fixed centre frequency
- UHF narrowband measurement with fixed frequency (or several fixed frequencies)

Figure 6 shows the **tuned UHF narrowband measurement with variable centre frequency**.

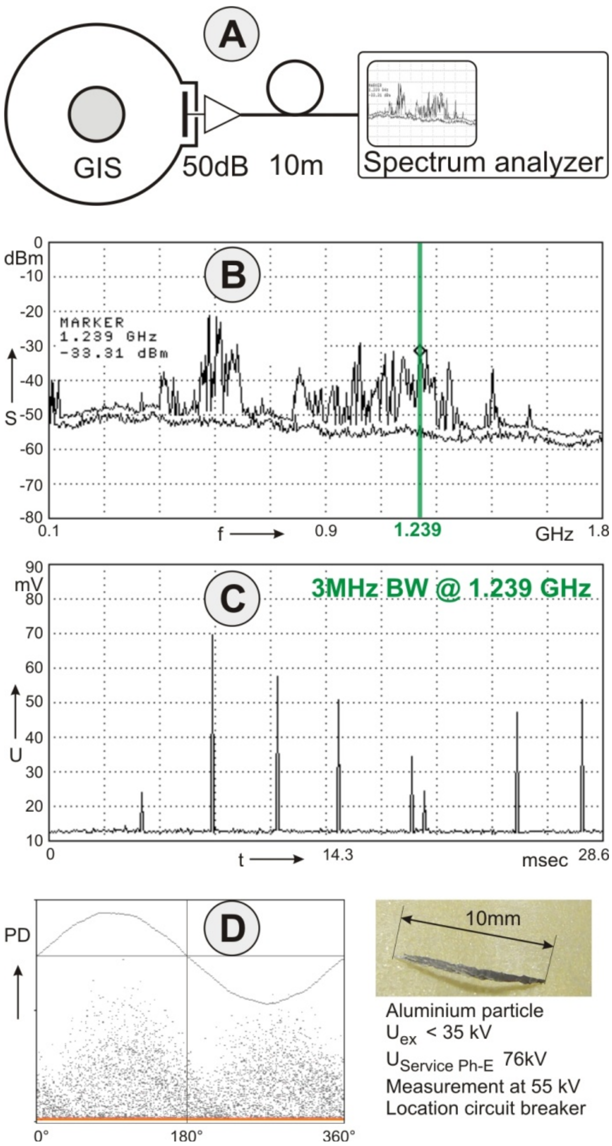

Fig. 6: Example of an tuned UHF narrowband measurement with variable centre frequency

The example shown is from an aluminium particle in a circuit breaker in a busbar coupler of a 132 kV GIS. The extinction voltage was less than 35 kV. The phase-to-ground operating voltage is 76 kV. The measurements shown were made at 55 kV.
A preamplifier is connected directly to the UHF sensor in order to prevent loss of sensitivity and reduce effects of external noise over the 10 m length of cable connected to the measurement equipment (Fig. 6A). The preamplifiers produce gain of approx. 50 dB over the bandwidth 0.1 - 2 GHz. Figure 6B shows the spectrum analyzer display of the measurement window of 0.1 - 1.8 GHz. The lower trace shows the noise floor, the upper trace shows the mixture of PD signal along with sporadic external interference, displayed linearly in frequency and logarithmically in amplitude (peak hold measurement with 1 minute integration time).
The frequency window in which PD can be measured is dependent on the combination of the defect and the employed sensor. Ideally a suitable measurement frequency window can be identified by simple observation, in which a high signal-to-noise ratio (SNR) results in high measurement sensitivity.
Once such a window is found, the spectrum analyzer's center frequency is centered on it, the bandwidth is set to e.g. 3 MHz, and the amplitude scaling switched to linear (Fig. 6C). The result is that the time-domain PD signal is coupled out at a measurement frequency in the UHF region with a high SNR. This signal can then be displayed on a conventional PD measurement system which is synchronized to the high voltage test waveform.
Once a phase-correlated pattern can be observed (Fig. 6D), it means a PD source synchronous to the test voltage is active and should be further investigated. If no phase-correlated pattern can be found, it is probable that the signal is an uncorrelated external interference which is irrelevant. Even under difficult conditions with high levels of ambient interference, with practice suitable frequency windows with good SNR can be found. Standardized equipment and methods can be employed to enable reproducible results across different measurement configurations and over the lifetime of the GIS to be obtained.
In the example shown, a 10 mm long aluminium particle in the circuit breaker of a bus bar coupling field was detected (Fig. 6D). The particle was active at normal operating voltage, and as such could well have led to a flashover under transient conditions.

Broadband UHF measurement with fixed center frequency is widely used especially for monitoring systems. A schematic diagram of the PD signal spectrum measured across several hundred MHz bandwidth is shown in figure 7.

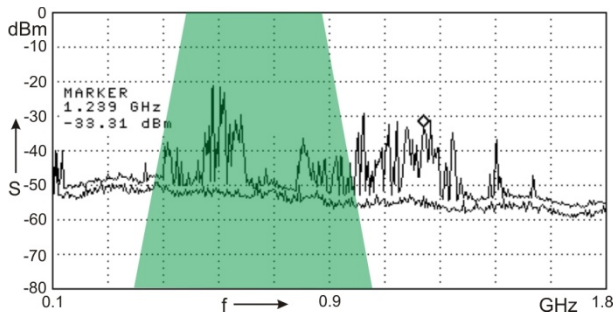

Fig. 7: Bandwidth of fixed broadband UHF method (schematic example)

Here the fixed broadband frequency spectrum is directly integrated and the signal variation displayed directly in phase-resolved pattern format. The frequency-domain amplitude envelope is not visible, only the phase-resolved pattern is seen. Also, such systems often have no preamplifier connected at the sensor.

Figure 8 contains a schematic diagram of the measurement domain of a **narrowband UHF-measurement with fixed frequencies.**

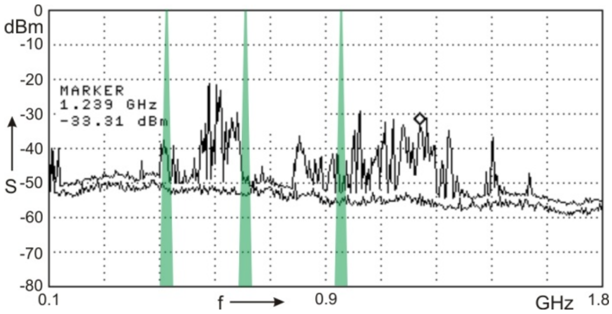

Fig. 8: Bandwidth of fixed narrowband UHF method (schematic example)

One or more narrow frequency windows are sampled and their output magnitude variation displayed directly as phase-resolved PD. Again, the frequency-domain spectrum is not visible here. There is the danger that the narrow frequency window may not exactly overlap the specific resonance frequencies of the received PD signal; in this case it is possible that even a PD source close to the sensor may not be seen.

The advantage of the fixed-frequency UHF methods is the possibility to display several channels of phase-resolved patterns simultaneously. The disadvantage of the fixed frequency method is that strong external interference sources such as radar, mobile telephones, corona, etc cannot be selectively tuned out. In areas with high levels of external interference, i.e. large substations or in built-up industrial or urban areas, the variable frequency narrowband method demonstrates a significant advantage in sensitivity and thus represents the most sensitive UHF-PD-measurement method.
A further advantage of this method over those displaying directly the phase-resolved PD pattern is that it enables the operator to quickly localize a PD source; since the higher frequency components in the PD signal undergo stronger attenuation, the presence of those higher frequency components can be used to determine which sensor is closest to a PD source.

5 PROPOSAL: TUNED MEDIUM-BAND UHF-METHOD

With the goal to combine the advantage of the high SNR of the narrowband UHF method (e.g. owing to the visual selection of a measurement frequency window) with the advantage of simultaneous multiple channels of the broadband fixed window method, a medium-band method is suggested which uses manual pre-selection based on the second step of the CIGRE sensitivity check. Figure 9 diagrams the signal relationships.

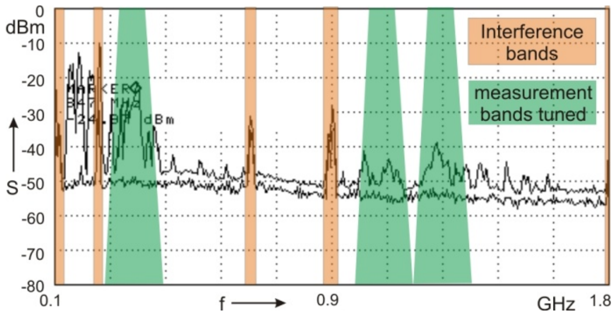

Fig. 9: Signal relationships of proposed tuned medium-band UHF method (schematic example)

The tuned medium-band UHF PD measuring system design consists of a bank of several manually tuned band pass filters, each of which has a nominal bandwidth of e.g. 50 - 150 MHz. These are arrayed across the frequency range of 100 to 2000 MHz. The individual center frequencies of the filters are tuned to correspond to the resonant frequencies of each PD-sensor when excited by the impulse generator in the second step of the CIGRE on-site sensitivity check. Interference sources can be selectively avoided.
Once the filters are set up, a high sensitivity PD measurement can be made in parallel on all sensors.
Using several tuned frequency bands, the probability of missing a resonant frequency of a PD-signal is low, plus the method additionally enables a first coarse localization of the PD-source based on the frequency dependent damping of the signals.
For the phase correlated display, the different frequency bands can be displayed individually, summed together or combined with e.g. histogram or bar graph indication for a quick overview.
In contrast to the narrowband method with fixed frequency, the medium band method integrates with good probability those signal frequency components which have shifted due to the difference in location between the actual PD source and the point of signal injection used to perform the CIGRE sensitivity check. The magnitude of the detected signal depends strongly on the location and to a minor degree on the orientation of the defect and the coupler [10 p77].

The main advantage of the proposed design is the combination of high sensitivity and the ability to select out interference signals while being able to tune to the most sensitive resonant frequencies of each PD-sensor.
This results in an optimized system design for PD-measurements, both for on-site tests and monitoring, enabling high sensitivity measurements even in difficult situations with the presence of strong interference sources.

6 PD MEASUREMENTS OF OLDER GIS

Older GIS installations undergo PD measurements due to various reasons:

- A defect is found while in service and PD test is performed following the repair, perhaps involving the entire station
- The possibility of systematic quality issues is established after the GIS has gone into service, it is decided to check whether these problems are present in the GIS installation.
- The installation has been in service for a long time and the overall insulation quality is checked in order to determine whether it should remain in service
- An older, existing installation is to be extended and the bus bars shall be concurrently tested.

For such situations the PD measurements using the UHF Method are the only alternative, particularly when the test can only be done while the installation is in service. Ideally UHF PD sensors are already installed, but external UHF sensors can also be used, depending on the GIS design and layout. These can be affixed at points where the internal field is accessible, such as inspection windows and locations on insulator flanges e.g. where there is an opening in the metal rim [13].
Figure 10 shows the application of an external sensor to the casting aperture of a GIS insulator

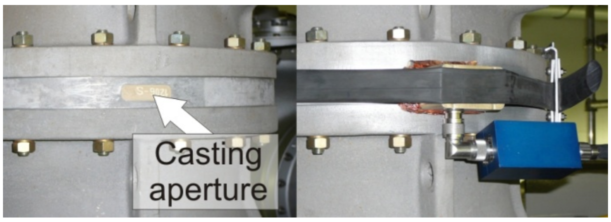

Fig. 10: Measurement with external UHF-PD-sensors: Left side casting aperture; right side PD sensor and preamplifier attached to the casting aperture

Figure 11 shows the spectrum of the 5 pC PD signal of a needle electrode measured at the external sensor (red) and measured at a standard internal UHF sensor (blue).

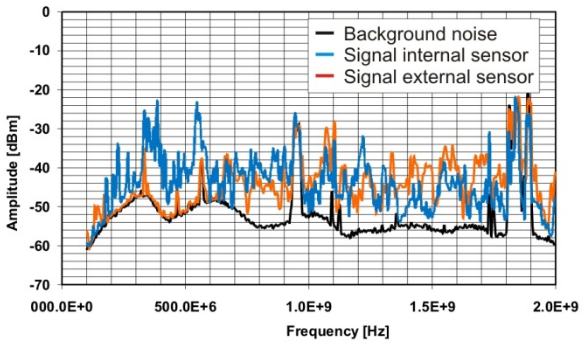

Fig. 11: Spectrum measured at an external sensor mounted at the casting aperture compared with spectrum measured at an internal sensor. PD-source: 5 pC emitted by a protrusion (needle).

It has been found that below 700 MHz, the external sensor is less sensitive than standard internal sensors, while at frequencies above 700 MHz optimized external sensors on insulator casting apertures can reach the sensitivity of internal UHF sensors. Similar results also have been found for sensors on inspection windows [14].
Because of the elevated signal attenuation in the higher frequency range (> 700 MHz), the spatial range for PD detection with external sensors is limited to a few meters. Therefore, external sensors are not considered to be an adequate replacement for internal sensors in commissioning tests because many more locations (3 - 5 sensors per GIS feeder and phase) are necessary, resulting in a high onsite test effort. However, external sensors may support the localization of a PD defect.

With the external UHF measurement set-up, an entire 30 year old 150-kV-GIS with 8 bays has been measured. Based on the performance of the CIGRE sensitivity check, an average measurement sensitivity of 2 pC was achieved (minimal sensitivity < 5pC).
Since the PD-measurement was made at service voltage, the integration time for PD measurements was set to 10 minutes in order to be able to detect intermittent PD-signals with low pulse repetition frequency and close to the inception voltage.
In conclusion, the installation of sufficient number of internal UHF-PD-Sensors in newly erected GIS is strongly recommended, since not every GIS type is equally suited for external sensors and the effort is much lower compared to the application of external sensors.

7 INTEGRATED TESTS

According to IEC 62271-203 (2003) [8, p91] every newly installed part of a GIS shall be subjected to a dielectric test on site.
In a typical non-ideal situation, not all parts of a GIS can be subjected to a high voltage test respectively gas compartments have to be opened again after the high voltage test. A typical example are voltage transformers which must be disconnected during the HV test if the test frequency is not high enough (typically > 80 Hz is required). If they are not equipped with a disconnector switch, the gas compartment must be opened in order to disconnect them. Similarly GIS cable connections are normally disconnected and the HV test performed up to the open link. Another example is when a HV test bushing must be installed on the bus bar in order to enable the HV test and which must subsequently be removed. Although the mentioned situation is not entirely comparable to a major repair, an unfortunate aspect of all of this is a failure rate up to 50% if no HV test is performed following repairs [3, p79].

The ideal situation occurs when all sections of the GIS can be tested and no further opening is necessary following the HV test. If the test frequency is higher than 80 Hz or the voltage transformers are designed to be tested at lower frequencies, then they can be test together with the GIS. This is highly recommended since experience indicates a relatively high failure rate for GIS voltage transformers.

Opening of the GIS following high voltage testing can be prevented e.g. using plug cable connectors (during the HV test the cable socket is closed with a dummy plug or filled with SF6 gas). Ideally the high voltage test supply can be fed into the GIS via an overhead line bushing or via a plug cable connection from the test set, designed to withstand the HV test voltage.
HV testing of the cable plus the plug-in connector in the GIS can be performed using e.g. an outdoor cable bushing or via a suitably designed cable junction box together with a test cable (figure 12).
Here it should be noted that GIS voltage transformers are typically disconnected for testing of long cables, or alternatively they are specially designed to withstand the lower test frequencies typically employed for long cable testing.

Figure 12 shows a test voltage injection via pluggable test cable.

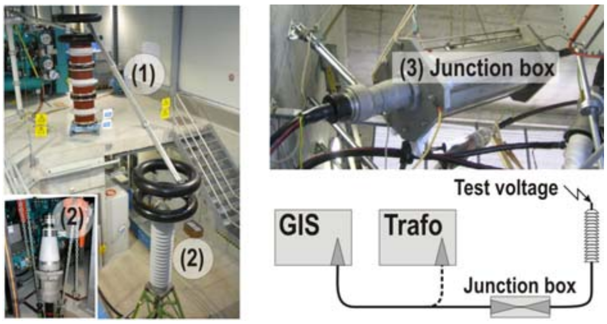

Fig. 12: Test voltage supply via pluggable test cable. Left side testing of GIS via test cable; right side testing of a cable via junction box and test cable.

The photo at left shows a HV test (1) feed via plug cable connection (2). The photo at right shows the test of a cable connecting GIS to a transformer. For this test, the cable was plugged into the GIS (disconnector switch opened), with high voltage being supplied via test cable and cable junction box (3) on the transformer side.
A further possibility is to perform an integral test of GIS, cable and transformer using a fully isolated star connection, details are described in [15].

The above mentioned scenarios correspond to the ideal case. Basically opening of gas compartments in GIS following the high voltage test should be prevented as much as possible, and all components connected to the GIS should be tested as far as their design limits allow. However, in practice, compromises to this ideal often must be made.

8 TRENDS

In recent years there is an increasing trend toward performing PD measurements at ever lower voltages in Switzerland. Recently UHF PD measurements have been made on 50 kV GIS and conventional PD measurements have been performed on 24 kV GIS. Among other reasons, this has happened based on PD defects being found which nonetheless withstood the HV test voltage. This demonstrates that the capability both to eliminate additional potential failure sources and gain additional information about the dielectric integrity is rated highly enough to accept the marginally higher costs of the additional PD measurement.
Furthermore, there is a clear trend toward PD measurements on older GIS in service along with verification testing of extensions.
Abroad, especially in Asia and the near east, the increasing trend toward installation of PD monitoring systems in GIS continues. This reflects the need and desire to assure the highest levels of reliability and availability of GIS on the part of the customer.

9 CONCLUSIONS

A PD measurement is not simply a measurement of a signal level on a sensor but encompasses a complex methodology including

- Preparation: formulation of the test program, acceptance criteria, test setup with PD-free test voltage generation,
- Measurement: Sensitivity check to verify a sufficient number of sensors, selection of measurement frequencies and amplification,
- If PD signals are found: Characterization, reproducibility, localization techniques
- Evaluation: determining the cause of the PD signal, assessing the implications, planning of follow-on measurement activities if required

The integration of a sufficient number of UHF sensors offers distinct advantages:

- High PD measurement sensitivity despite the presence of significant interference signals
- The possibility of dielectric integrity measurements in service following repairs or discovery of systematic faults, and at the end of the expected service life.
- Precise localisation with using time-of-flight measurement techniques

Since there is no correlation between the PD level detected and the flashover voltage of the defects (e.g. critical defects like particle on a spacer can show PD level of only 1 pC) the PD measurement must be as sensitive as possible.
Among the present UHF-methods, the narrow band method with visual selection of the measurement frequency together with a broadband preamplifier directly mounted at the PD sensor allows the most sensitive measurements. Due to the frequency window selection process, only one sensor at a time can be measured.
The proposed tuned medium-band UHF-Method offers the possibility to selectively avoid interfering frequencies but also not to miss resonant frequencies at a specific PD sensor (which are interdependent on the defect and its location) due to sufficient bandwidth. A pre-tuning of each individual sensor location based on the second step of the CIGRE sensitivity check on site allows simultaneous measurement of many sensor locations with optimized settings.

To measure the dielectric integrity of older GIS, external UHF sensors can be applied. Typically, internal UHF sensors are more sensitive than externally applied sensors below approx. 700 MHz; above this, optimized external sensors can approach the sensitivity of internal sensors.
Owing to higher signal attenuation above 700 MHz, detection of PD with external sensors is practicably limited to a few meters distance. Therefore, external sensors are not considered to be an adequate replacement for internal sensors in commissioning tests because numerous measuring locations (3 .. 5 sensors per GIS feeder and phase) are necessary, resulting in high onsite test effort. However, external sensors may support the localization of a PD defect.

Integral testing enhances overall quality by helping to avoid subsequent reopening of the GIS after the test and also by testing interfaces and components with increased failure risk.
The increasing trend toward performing PD measurements at ever lower voltages shows the need and desire to assure the highest levels of reliability and availability of GIS on the part of the customer.

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10 REFERENCES

[1] CIGRE Working Group B3.17, GIS state of the Art 2008, Brochure 381, June 2009
[2] IEC-Publication 60071-2, Insulation co-ordination; Part 2; Application Guide, Third edition 1996-12
[3] CIGRE Joint Working Group 33/23.12 Insulation co-ordination of GIS; return of experience on site tests and diagnostic techniques; Electra No 176, February 1998
[4] T.M. Chan, F. Heil, D. Kopejtkova, P.O. Connell, J.-P. Taillebois, I. Welch; Report on the second international survey on high voltage gas insulated substations (GIS) service experience CIGRE 23-102, 1998
[5] N. Fujimoto, S. Rizzetto, J.M. Braun; Improved PD testing of solid dielectrics using x-ray induced discharge initiation IEEE Electrical Insulation Magazine Vol. 8, No 6 November / December 1992
[6] M. Miyashita, C. Nishida, M. Kamei, G. Ueta, S. Kaneko, S. Okabe; Insulation characteristics of micro size defects inner epoxy; 16th ISH Cape Town, South Africa 24. – 28. August 2009
[7] S. Adili, C.M. Franck, H. Fuhrmann; Pulsed x-ray induced partial discharge measurement (PXIPD), XVIII International Conference on Gas Discharges and Their Applications (GD 2010), Greifswald, Germany, 5 – 10 September 2010
[8] IEC-Publication 62271-203; High-voltage switchgear and controlgear – part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV; first edition 2003-11
[9] T. Hinterholzer; W. Boeck; Breakdown in SF6 influenced by corona-Stabilization; conference on electrical insulation and dielectric phenomena, Victoria, British Columbia, Oct. 15-18, 2000, Vol. I, pp. 413 – 416
[10] CIGRE task force 15/33.03.05 Partial discharge detection system for GIS: Sensitivity verification for the UHF method and the acoustic method; Electra No 183, April 1999

[11] A.J. Reid, M.D. Judd, B.G. Stewart, R.A. Fouracre, S. Venkatesan; Correlation between RF energy and IEC 60270 apparent charge for selected partial discharge source geometries; 15th ISH Ljubljana, Slovenia, August 27-31, 2007; T7-531
[12] A.J. Reid, M.D. Judd; High Bandwidth measurement of Partial Discharge Pulses in SF6; 14th ISH Beijing, China, August 25-29 2005; G-012
[13] S. Neuhold, T. Heizmann, R. Bräunlich, D. Köchli, U. Riechert, C. Dehne; Experience with UHF PD detection in GIS using external capacitive sensors on windows and disk-insulators; 15th ISH Ljubljana, Slovenia, August 27-31, 2007, T7-480
[14] 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
[15] G. Storf, T. Heizmann; Teilentladungs-erfassung an Hochspannungskabelend-verschlüssen und –muffen vor Ort: Methoden und Erfahrungen; ETG Tagung Diagnostik elektrischer Betriebsmittel; Köln, Germany, March 9-10, 2004

Zusammenfassung: Aufgrund der geforderten hohen Zuverlässigkeit und Langlebigkeit von GIS sind strenge Qualitätskontrollen insbesondere bei der abschließenden Abnahmeprüfung von hoher Wichtigkeit. In diesem Beitrag werden die Prüf und Meßtechniken für dielektrische Tests an GIS vor Ort vorgestellt und eine neue UHF-TE-Meßmethode vorgeschlagen. Ausgehend von den Fehlertypen und ihrer Detektierbarkeit werden durch die Fachgremien spezifische Prüfkombinationen empfohlen um möglichst alle Fehlertypen zu detektieren. Insbesondere die Wechselspannungsprüfung kombiniert mit einer möglichst empfindlichen TE-Messung hat sich als Standard durchgesetzt. Die Eignung der verschiedenen TE-Meßtechniken werden diskutiert und spezifisch auf die Varianten der UHF-TE Messung eingegangen. Um ein Optimum an Empfindlichkeit, Störsicherheit und simultaner Messung zu erreichen wird eine Mittel-Band UHF Methode mit einstellbarer Mittenfrequenz vorgeschlagen. Die integrale Prüfung erlaubt eine weitere Verbesserung der Prüfqualität durch Vermeiden von nachträglichem Öffnen der GIS nach der Hochspannungsprüfung und Prüfen von Schnittstellen zur GIS und Komponenten mit erhöhtem Ausfallrisiko. Die Nachfrage nach einer Überprüfung des dielektrischen Zustandes von älteren GIS Anlagen mit TE Messungen hat zugenommen. Es werden die Anwendung von externen UHF TE Sensoren und ihre Eigenheiten diskutiert.

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