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APPLICATION OF PARTIAL DISCHARGE DIAGNOSTICS IN GIS AT ON-SITE COMMISSIONING TESTS

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Abstract

Related to AC commissioning tests and on-line monitoring, partial discharge (PD) diagnostics in GIS have received substancial interest during the last years. The paper presents recent experience with on-site PD detection in complete GIS using electrical methods. In particular, the conventional PD method (IEC 60270) is compared with the VHF/UHF method. For various GIS types (single and three phase systems) special wide-band sensors have been developed for the VHF/UHF range and their applicability examined under site conditions. Taking into account the specific signal transfer behaviour in a complete GIS, optimal sensor positions are proposed. The real PD detection sensitivity was examined on-site by inserting artificial defects in the GIS. Finally, both PD methods were applied to commissioning tests of 9 GIS installations (U_m = 72.5 kV to 245 kV). The on-site experience is discussed and a PD test procedure proposed.

Key words

GIS, HV site test, partial discharge, PD detection, UHF method, VHF method, artificial defects, HV commissioning tests

1. INTRODUCTION

It is important to check the dielectric integrity of a fully assembled GIS after erection on site. Today, an AC test combined with PD detection is the most frequent test procedure for a GIS installation.

There is a broad consensus that for all system voltages this test procedure is the most effective provided that the on-site PD methods used have sufficient detection sensitivity [1].

For PD diagnostics in GIS, various methods are available today with their known practical problems and limitations e.g. [2, 3, 4]. The use of electrical PD methods provides some practical advantages in particular at frequencies in the VHF and UHF range (background noise suppression). However, for these frequencies the signal transfer behaviour of a GIS and the sensors (coupling devices) have a decisive influence on the sensitivity of the detection method. Results obtained in small laboratory set-ups are obviously not directly transferable to a full size GIS. Therefore, this behaviour has to be individually investigated for each design of GIS. Regarding the detection sensitivity, in particular it is necessary to examine systematically type and position of PD sensors.

Only little information is available about field experience and practical use of the VHF/UHF method e.g. [5,6,7,8]. Therefore, on-site investigations have been carried out with the aim

a) to clarify the typical signal transfer behaviour of various GIS designs using special wide-band sensors in the VHF/UHF range and
b) to compare the PD detection sensitivity of the VHF/UHF method with the conventional PD method in a complete GIS installation (see Annex).

Additionally, PD diagnostics was applied during commissioning tests of 9 GIS installations (single and three phase encapsulated systems) with U_m ranging from 72.5 kV to 245 kV using both PD methods, conventional and VHF/UHF. On the basis of this experience practical recommendations are given concerning the suitability of electrical PD method under on-site conditions, optimal sensor positions in a GIS and the PD test procedure.

2. ON-SITE PD DETECTION IN GIS

2.1 Methods for PD detection

The PD detection methods used for the commissioning tests and the investigations reported in this paper are restricted to electrical methods. The acoustic method is also a valuable tool for PD-detection at commissioning and periodic in-service tests, in particular for localizing free moving metallic particles [9].

As PD causes electrical phenomena in a wide frequency

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range the methods applied may be characterized according to their typical frequency range used for the measurements:

Conventional (IEC 60270)	50 kHz...1 MHz
VHF	30 MHz...300 MHz (TEM wave mode)
UHF	300 MHz...approx. 2 GHz (TEM-, TE-, TM- wave modes)

2.2 Technical specifications

The technical specifications of the methods used in this paper are the following:

Conventional PD-method

Coupling capacitor: C_k = 500 pF

Narrow-band PD-detector and coupling device: 40 kHz...1 MHz

PD impulse processing for phase resolved measurements.

VHF/UHF-method

The schematic diagram of the VHF/UHF measuring equipment is shown in Fig. 1:

- Wide-band amplifier (typical 0.1-1000 MHz, + 35 dB) directly connected to the sensors.
- Spectrum analyser (9 kHz-1.8 GHz) in the "spectrum scanning mode" or in the "zero span mode" at a given centre frequency f_c or RF detector (wide-band demodulator).

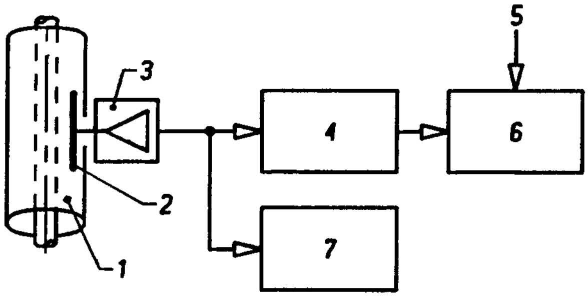

Fig. 1: Set-up for VHF/UHF measurements
1 GIS, 2 PD sensor, 3 preamplifier, 4 spectrum analyser or wide-band demodulator, 5 sync. signal from voltage divider; 6 phase resolved PD analyser (PRPDA), 7 digital oscilloscope

In order to realize a **wide-band coupling device** with a low cut-off frequency (< 100 MHz) flat sensors with large diameters were installed in the GIS. The capacitances to HV electrode are typically less than 1 pF.

The sensor geometries adapted for the various designs of GIS are:

single phase system, GIS type A: (U_m = 72,5 kV-245 kV)	ø = 170 mm, capacitance to ground (stray) approx. 40 pF
single phase system, GIS type B: (U_m = 245 kV-300 kV)	ø = 240 mm, capacitance to ground (stray) approx. 80 pF
three phase system, GIS type C: (U_m = 72,5 kV-145 kV)	ø = 340 mm, capacitance to ground (stray) appr. 100 pF

These sensors have a wide frequency range (<100 MHz...>1 GHz). This allows a sensitive PD detection even under high noise conditions due to the flexibility of choosing frequencies also in the VHF and UHF band.

2.3 PD signal transfer/attenuation and calibration in the VHF/UHF range

Behaviour of a busbar system

The typical signal transfer characteristics in the frequency domain from sensor to sensor installed on busbars of three different GIS designs are shown in Fig. 2 and 3 respectively. In the situations considered here at least two disconnectors and several feeder branches were installed along the propagation path.

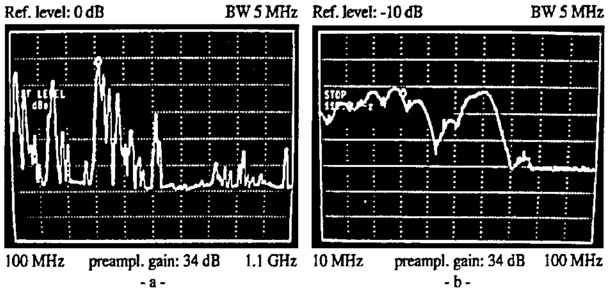

Fig. 2: Signal transfer characteristics in the frequency domain of real busbar systems
- a - single phase system of GIS type B (0.1 ... 1.1 GHz) distance between sensors approx. 6.5 m
- b - three phase system of GIS type C (10...100 MHz) distance between sensors approx. 24 m

Single phase encapsulated system:

The busbar of GIS type A shows a marked attenuation of frequencies in the range between approx. 350 MHz and 550 MHz (see Fig.3a, S1–> S2), whereas the busbar of GIS type B attenuates higher frequencies, i.e. higher than approx. 550 MHz (see Fig. 2a). Both sensor systems show pronounced resonances in the UHF-range (higher wave propagation modes) even at longer busbar systems (> 20 m).

Three phase encapsulated system:

The busbar of GIS type C exhibits a quite different behaviour (see Fig. 2b). In the situation studied, frequencies above approx. 80 MHz were completely attenuated. Further investigations have revealed that this attenuation effect is related to the design of the GIS (gas compartment separation using metallic insulator supports). Regarding the attenuation effect it was found that already after three such supports frequencies above 100 MHz were completely suppressed.

It should be noted that the transfer characteristics measured at a short busbar section (l = 2 m) with two insulating spacers do not show a marked attenuation over a wide range of frequencies up to approx. 1 GHz. This is the situation for most of the experimental results obtained in laboratories e.g. [10, 11]. It is obvious that in a real busbar configuration the signal transfer characteristics can deviate significantly from results obtained in laboratory experiments.

Behaviour of a complete installation
In a complete GIS, components such as circuit breakers, disconnectors etc. have additional attenuation effects on the PD signal propagation. This behaviour is of particular importance for the optimal sensor positioning in a GIS. Fig. 3 shows results of signal transfer characteristics obtained in a 110 kV GIS of type A consisting of 5 bays and a single busbar system (see Annex). The comparison of results (Fig. 3a and b) illustrates clearly that the transfer function obtained at the busbar (S1 –> S2) is not representative for the signal transfer to the sensor placed at the cable feeder (S1 –> S3). The additional damping effect caused by the circuit breaker results in a significant decrease of sensitivity at frequencies above 300 MHz.

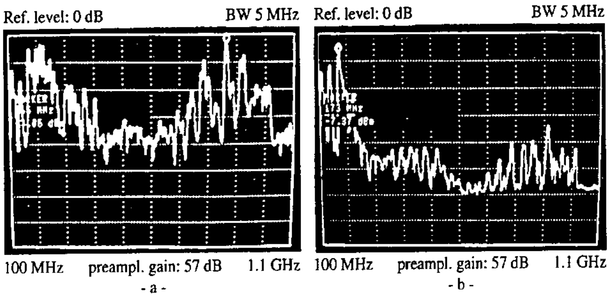

Fig. 3: Signal transfer characteristics in the frequency domain (100 MHz ... 1.1 GHz) in a complete GIS of type A with sensors at different positions (single line diagram and sensor positions see Annex).
- a - S1 -> S2 (busbar only)
distance between sensors approx. 10.5 m
- b - S1 -> S3 (busbar + cable feeder)
distance between sensors approx. 14.5 m

Investigation with artificial defects
In order to check this attenuation influence two test compartments A and B were connected to the 110 kV GIS as shown in the Annex. The detection sensitivity was investigated by inserting various types of defects into the test compartments. The results are summarized in the Annex.

From these results conclusions concerning absolute detection sensitivity and comparision with the conventional PD method can be drawn as discussed in detail in chapter 3.

2.4 Calibration of VHF/UHF measurements

To quantify the detected PD intensities, a calibration of the VHF/UHF method in terms of apparent charge according to IEC 60270 would be desirable.

For the calibration of the VHF/UHF measurements an attempt was made to determine the signal transfer characteristics between pairs of sensors (see section 2.3). A voltage step with an amplitude U_O (typically 20-50 V) and nanosecond rise time is applied to one sensor while the response of the second sensor is analysed with a spectrum analyser. This procedure allows to determine the frequency bands in which signals are transmitted through the GIS. On the basis of the capacitance C_O of the sensor to the HV conductor an estimation of the injected charge q_O has been made ($q_O = U_O \times C_O$).

For certain defects, it can be demonstrated by comparison that the charge values determined according to the procedure above are in the same order of magnitude as the values obtained by the conventional PD method.

However, recent investigations [12] have shown that for a narrow-band detection system the correct integration of apparent charge from PD impulse currents in SF6 is limited to frequencies up to a few MHz. At higher frequencies the PD spectrum depends not only on the PD impulse shape but also on factors such as type and position of sensors and type and location of a defect. Hence, for the VHF/UHF method a definition of the PD intensity in terms of apparent charge is not useful (see Annex, example I).

3. EXPERIENCE FROM ON-SITE COMMISSIONING TESTS

Since 1991 some commissioning tests for GIS installations of GEC ALSTHOM have been carried out by FKH in Switzerland using the VHF/UHF method in combination with a series resonant test circuit [13]. With this test circuit it was possible to perform commissioning tests with complete installations including voltage transformers and cables. To avoid saturation effects of the voltage transformer the frequency of the test voltage was > 90 Hz.

Table 1 presents data of the installations tested. For these tests (except No. 8) the conventional PD method with totally encapsulated test circuit have been applied additionally. In some cases both methods have been used simultaneously.

Table 1: GIS installations tested

No.	type of GIS	bays	busbar system	feeder		test voltage at site kV	background noise level pC 2)
				cable term.	SF6/air bushing		
1	220 kV / B	5	1	5	-	370	< 1
2	150 kV / A	5	2	4	-	325	0.5-1.5
3	132 kV / A	9	2	4	4	325	1.5-2.5 < 3.5 1)
4	132 kV / A	5	1	3	2	325	1.5-2 < 2.5 1)
5	110 kV / A	12	2	10	-	275	1-1.5
6	110 kV / A	5	1	5	-	275	< 1
7	110 kV / A	4	2	2	2	230	< 1 < 1.5 1)
8	65 kV / C	16	2	15	-	140	—
9	52 kV / A	13	2	11	-	140	< 1

1) SF6/air bushing included in test circuit
2) completely encapsulated test arrangement with SF6 insulated test transformer and conventional PD method

The typical background noise levels are reported in Table 1. It can be seen that for commissioning tests with completely encapsulated test circuit the on-site noise level in terms of apparent charge was very low: e.g. for GIS with cable terminations only up to 1.5 pC. In case of SF6/air bushing sections it was less than 3.5 pC. It should, however, be noted from other experience that higher noise levels may be obtained, but only in rare cases.

When an external test circuit (conventional testing transformer or series resonant test set) is applied for commissioning tests, a higher external noise level has to be expected. The reason is the connection of GIS to the external AC test set via a SF6/air bushing. In such cases the sensitivity of the conventional PD method is reduced: The use of the VHF/UHF method may then be the only way to perform sensitive PD detection.

3.1 PD test procedure

PD detection/measurement

For PD detection/measurement the following measuring procedures have been applied:

Conventional PD method: PD measurements and calibration according to IEC 60270. PD amplitudes and phase relationship of PD pulses relative to the test voltage were recorded.

The testing of the GIS was carried out in sections to keep the load capacitance C_ℓ for the test transformer low. In addition, this allows an easier localisation of defects. In most cases, the ratio C_k/C_ℓ lays between 1 and 0.25.

VHF/UHF method: For the PD signal demodulation and noise suppression, the measurement set-up indicated in Fig. 1 has been used. The spectrum analyser is operated in both, the "spectrum scanning mode" (typical resolution bandwidth 5 MHz) and in the "zero span mode" at a given centre frequency f_c. The following procedure is used: Before the application of the test voltage, a spectrum of the background noise is recorded in the scanning mode using the peak hold function. During the test, the spectrum is continuously scanned and deviations from background noise are recorded. If any deviation from background noise is detected, the spectrum analyser is switched to "zero span mode" at a suitable centre frequency to check whether the detected signals are correlated to the test voltage. This is done by using a digital impulse processing system (phase resolved PD analyser / PRPDA, see Fig. 1).

Because of the complex PD signal transfer characteristics in a real GIS installation, a selection of the centre frequency based on simulation experiments between sensors only cannot assure that the spectrum of a real PD signal received from a PD sensor has significant frequency content in the frequency range around the selected centre frequency. Therefore, at least two or more centre frequencies have to be selected for zero span measurements.

In some cases wide-band RF-detectors have been used. Thus, a continuous measurement of all PD activity in a very wide frequency range (0.1 ... 2 GHz) was possible. However, the discrimination between PD signals and background noise is then more difficult.

Acceptable PD level

According to CIGRE WG 33/23-12 [1] PD measurements are recommended at a test voltage level $U_{testPD} = 0.8 \times 0.36$ LIWL = 0.29 LIWL (LIWL = lightning impulse withstand level). The highest permissible PD should not exceed a value of about 5 pC (apparent charge according to IEC 60270) or equivalent. If the PD noise level on site is too high, i. e. > 50 % of the highest permissible PD level, a lightning impulse test should be carried out instead of the PD measurement.

However, the practical experience reveals the limits of the proposed procedure:

- There are typical types of defects, even critical defects, which may produce PD intensities of much lower PD values than 5 pC, e.g. metallic particles on spacers (< 1 pC) or corona stabilized protrusion on the HV electrode (~1 pC), see Annex.
- Applying the VHF/UHF method for PD detection may have advantages regarding the detection sensitivity in noisy environment. However, the detected PD quantities cannot be calibrated in terms of an apparent charge. This is supported by theoretical and experimental investigations recently published [12]. Hence, a limiting value equivalent to 5 pC cannot be defined for the VHF/UHF method.
- Lightning impulse tests on-site have to be planned and accepted by the customer at an earlier stage of project. It is therefore not realistic to change the testing procedure on-site if the PD test has failed due to a too high background noise level.

According to the results presented in Table 1, the detection sensitivity in complete GIS was typically well below the "limiting" value of 5 pC. In the case that imperfections of the GIS were detected the defects were carefully identified and localized. On the basis of the type and location of a defect found, a risk assessment was carried out and decided whether the GIS had to be opened or not, even if the PD level was well below 5 pC.

Conditioning

The detection of free moving particles must be carried out carefully, also for GIS designs of lower nominal voltages. Free moving particles of critical size may be removed from the high field regions by a conditioning sequence. Nevertheless, sometimes cleaning flashovers may occur. According to [1] such flashovers are not considered as failure (no opening of the GIS) under the condition that the full test voltage can be successfully applied afterwards.

To reduce the risk of cleaning flashover to a minimum, the test voltage increased in steps (e.g. of 5 %, starting at 1.2 x U_0, see Fig. 4) until PD measurements show unambiguous PD pattern of free moving particles or other defects (see Annex). The conditioning phase may then be continued at the same voltage level for a defined duration.

3.2 Detection sensitivity for typical defects

The defects detected during commissioning tests are summarized in Table 2.

Free moving particles:

They are the predominant defects in a GIS. Particles with lengths of 3 mm and bigger were detected with both methods. With the VHF/UHF method the position of sensors does not limit the detection of free moving particles although the sensitivity can be different (see Annex, example I).

Table 2: Defects detected during commissioning tests of 9 GIS installations (U_m = 72.5 ... 245 kV)

Defect pattern	No. of occurance	Observations, findings	Actions
free moving particles	3	⚡ during increase of test voltage without conditioning; retesting at 100 % test voltage level -> o.k.	no opening
	3	3-8 mm alu/copper particles in a circuit breaker; defects not removeable by conditioning, 5-20 pC	opening a circuit breaker particles found and removed
	1	12 mm isolated copper wire in voltage transformer up to 15 pC; after conditioning the PD level decreased to a level < 2 pC	opening VT wire found in a particle trap
fixed particle on HV-conductor	1	3 mm steel particle pinched between HV-conductor and spacer on the busbar, 3-4 pC	opening busbar particle found and removed
defect in an insulating part	1	void in a pivoting lever of a sectionalizer at busbar, 4-5 pC	opening of the sectionalizer; change of pivoting lever; void found by x-ray test
defect in a spacer	1	defect localized in a busbar disconnector; up to 8 pC, PD pattern similar to a delamination in a spacer	opening of the disconnector; change of insulating parts; defect could not be confirmed by post-test in laboratory; defect remained unknown

Fixed particle and protrusion on HV electrode:
If corona stabilsation does not take place, a sensitive detection with both methods is possible (see Annex, example II). In the case of a corona stabilisation only a few intermittent PD pulses of low intensity are detected at higher test voltages (see Annex, example III). In most cases, a breakdown can not be avoided due to the small difference between PD onset and breakdown voltage. The occurence of such defects is very rare in practice.

Defect in solid insulation (e. g. spacers):
Typical examples are voids or delamination in cast resin material. Such defects can be clearly detected with both methods provided that the test voltage is applied for sufficient time (several minutes).

Metallic particle on the surface of spacer:
Even in the case of a very low noise level (e. g. < 1 pC) and careful application of both methods a detection of this type of defect is very difficult (see Annex, example IV). More precise information about detection sensitivity cannot be given because factors such as position and orientation of particle on the spacer (e.g. at the point of maximum tangential field, direction of field gradient) essentially affects the detection. For PD onset even higher test voltage levels are necessary compared to the corona stabilised protrusion on the HV electrode. Therefore the margin between PD onset and breakdown is very small. In most cases breakdown occurs without detectable PD activity.

Particles on a spacer surface may not be in a critical position during commissioning tests. However, they may become critical in service e.g. due to displacement on the spacer. Today, PD detection sensitivities are at their limit for this type of defect.

4. RECOMMENDATIONS

On the basis of the results presented above, the following recommendations may be given:

4.1 Selection of PD method

Conventional PD method
For typical defects, the conventional method offers sufficient on site detection sensitivity even in cases where SF6/air bushings are integrated in the GIS. The necessary conditions are: a totally encapsulated test circuit and PD pulse processing for phase resolved measurement.
Under these conditions, the conventional PD method may be preferably applied for the following GIS configurations:

- GIS installations equipped with cable feeders only
- GIS installations equipped with SF6/air bushings if the background noise level for the bushing section is not higher than some pC and the origin of noise can be identified by the phase resolved pattern.

VHF/UHF method
If an external test circuit (e.g. series resonant test set) is used, the VHF/UHF method may be preferably applied for PD detection in the following situations:

- Voltage transformers and cables have to be included in the HV commissioning tests (frequency of test voltage >50 Hz).
- GIS installations equipped with SF6/air bushings where a background noise level much higher than 5 pC may be expected.
- GIS installations already equipped with UHF sensors for on-line monitoring (recording of reference pattern).

Taking into account the sensor types and their signal attenuation characteristics described in section 2.2 and 2.3, the following recommendations concerning sensor positions in a GIS can be given for providing a sufficient detection sensitivity:

Single phase encapsulated systems (GIS types A and B):

- Two sensors per phase on the busbar system installed near both ends; even for long busbars, two sensors are sufficient.
- An additional sensor per phase at the end of each feeder in order to take into account the particular signal attenuation behaviour of circuit breakers (see section 2.3).

Three phase encapsulated systems (GIS type C):

- If the design uses metallic supports for insulators as gas barriers a high attenuation in the UHF range is observed (see Fig. 2 b). In this case the application of the UHF method is not recommended.
- As an alternative to the conventional PD method, the

VHF method can be used for PD detection.

For on-line monitoring of a GIS only the UHF narrow-band method can be recommended. The same sensors and similar detection equipment may be used. Results recently published [11] have, however, demonstrated that not all significant defects are detectable under in-service conditions by an on-line monitoring system using the narrow-band UHF method. This is not due to the detection method but is related to the fact that for some defects the PD onset voltage is higher than the service voltage).

4.2 Proposed PD test procedure

A three step test procedure is proposed for commissioning tests (see Fig. 4):

Conditioning phase

- Objective: removing of free particles
- Applied AC test voltages:
  - start at the conditioning voltage U_c, e.g. $U_c = 1.2\ U_o$ with $U_o = U_r/\sqrt{3}$ (U_r = system voltage)
  - gradual increase of voltage to the withstand test voltage in suitable steps; voltage levels and duration according to manufacturer's recommendations.
- Continuous PD measurement for breakdown warning
- Actions:
  if unambiguous PD pattern appear
  - continue test as long as PD activities remain low or
  - if PD activity increases with test voltage: risk assessment on the basis of type and location of defect; remove defect; repeat test.

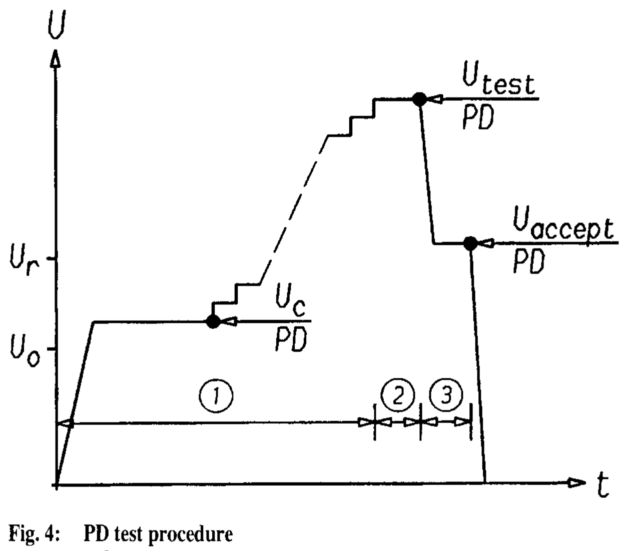

Fig. 4: PD test procedure
① conditioning phase
② HV withstand test (see text)
③ PD acceptance test (see text)

HV test

- Objective: proof of AC withstand capability of GIS
- Applied AC test voltage:
  $U_{test\ on\text{-}site} = 0.36 \times LIWL$
  duration: 1 min.
- PD measurement for breakdown warning
- Actions:
  - if breakdown occurs, localize and remove defect, repeat test

PD acceptance test

- Objective: proof that GIS is PD free for all AC operating conditions
- Applied AC test voltage: $U_{accept} = K_E \times K_S \times U_r/\sqrt{3}$
- K_E (earth fault factor): 1.4 solidly earthed system; $\sqrt{3}$ isolated neutral or resonant earthed system
- K_S (safety factor, IEC 71.1): 1.25 for GIS
- Acceptable limit: PD level ~ background noise level (a few pC) and PD extinction voltage above U_{accept}
- Actions if test fails: remove defect; repeat test.

The PD acceptance criterion is based on the requirement that the PD extinction voltage is above the required power frequency withstand voltage U_{rw} in service, i.e. $U_{rw} = U_{accept}$. This criterion is applicable in particular to free moving particles and defects in solid insulation. Both types of defect are not sensitive to lightning impulse tests.

The proposed PD acceptance criterion is equally applicable for both, the conventional PD method and the VHF/UHF method.

5. CONCLUSIONS

HV commissioning tests with 9 GIS substations (U_m = 72.5 to 245 kV) have been carried out using the conventional PD method and the VHF/UHF method. The results may be summarized as follows:

- The conventional PD method and the VHF/UHF method offer sufficient sensitivity for commissioning tests of a complete GIS. The detection sensitivity is equivalent in totally encapsulated test situations.
- Using a completely encapsulated test circuit, the background noise level was < 1...2.5 pC; for sections with integrated SF6/air bushings up to 3.5 pC. Using external test circuits in the same GIS a higher noise level is to be expected. The sensitivity of the conventional PD method is then reduced. The VHF/UHF method is a good alternative in noisy environments.
- The specific wide-band behaviour of special sensors (<100 MHz ... >1 GHz) offers a high flexibility in the VHF/UHF frequency band if selective bandpass filters are used for noise suppression.
- The calibration of the VHF/UHF method in terms of apparent charge is not possible. There is no direct correlation between the quantities measured with the conventional PD method and the VHF/UHF method.
- Detection sensitivity for typical defects:
  - no detection problems for: free moving particles, floating electrodes, defects in solid insulation and protrusions on HV electrode without corona stabilisation
  - limited detection for: metallic particles fixed on spac-

er surface or corona stabilized protrusions on HV electrode (PD levels ≤ 1 pC). In many cases, PD diagnostics cannot avoid a flashover.

- The recommended positions of sensors in the GIS designs investigated in this paper are: two sensors on the busbar near the ends; an additional sensor in each feeder.
- The PD test procedure should include three steps: conditioning phase, HV AC withstand test and PD acceptance test.
- The acceptance criterion for the PD test is based on the insulation coordination (required AC withstand voltage U_{rw} in service). In all cases, the PD extinction voltage of a GIS has to be above the U_{rw} level.

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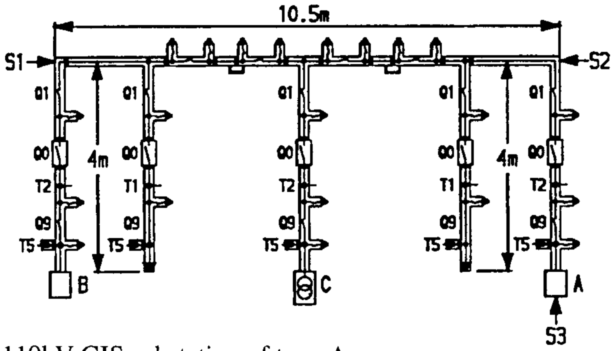
ANNEX:
PD detection sensitivity for various types of defect in a 110 kV GIS substation of type A VHF/UHF method versus conventional PD method



110kV GIS substation of type A
S1, S2, S3 sensors, C GIS test transformer + C_k
A, B test compartments for defects

I Type of defect: 5 mm alu particle (ø ~ 0.5 mm) free moving on the enclosure

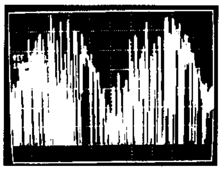
Location: test compartment B

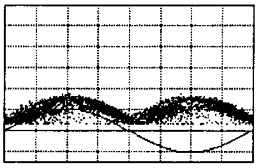
Test voltage level: 35 kV

UHF-method (preampl. +57 dB) Ref. 10 mV BW 5 MHz

Conventional PD method Background noise: < 1 pC Ref. 2.5 pC/div.

S2

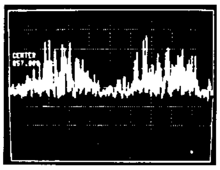




f_c = 862 MHz q ~ 4 pC

Ref. 1 mV BW 5 MHz

S3



f_c = 862 MHz

Remark: Detection independent on sensor position

II Type of defect: 5 mm alu particle (ø ~ 0.5 mm) fixed on HV electrode

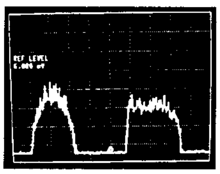
Location: test compartment A

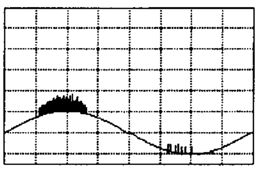
Test voltage level: 100 kV

UHF-method (preampl. +57 dB) Ref. 5 mV BW 5 MHz

Conventional PD method Background noise: < 1 pC Ref. 2.5 pC/div.

S3





f_c = 643 MHz q ~ 2 pC

Remark: No measurable signal at sensor S2

III Type of defect: sharp protrusion on HV electrode

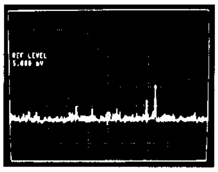
Location: test compartment A

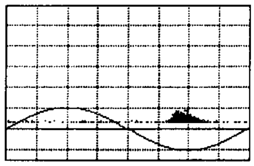
Test voltage level: 210 kV

UHF-method (preampl. +57 dB) Ref. 5 mV BW 5 MHz

Conventional PD method Background noise: < 1 pC Ref. 2.5 pC/div.

S3





f_c = 460 MHz q ~ 1 pC

Remark: intermittent PD impulses, corona stabilisation; at 234 kV sudden breakdown after 30 sec. without a marked increase of the PD.

IV Type of defect: 5 mm alu particle (ø ~ 0.5 mm) fixed on spacer surface at critical field location in tangential direction

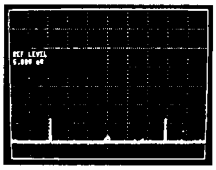
Location: test compartment B

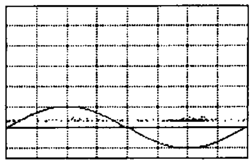
Test voltage level: 235 kV

UHF-method (preampl. +57 dB) Ref. 5 mV BW 5 MHz

Conventional PD method Background noise: < 1 pC Ref. 2.5 pC/div.

S1





f_c = 440 MHz q < 1 pC

Remark: only few PD impulses with low amplitude; not measurable with conventional PD method; at 260 kV sudden breakdown after approx. 2 min. without a marked increase of the PD.

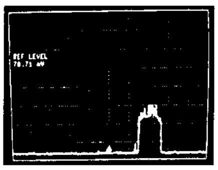
V Type of defect: External corona, metallic screw on shielded electrode of a SF6/air bushing

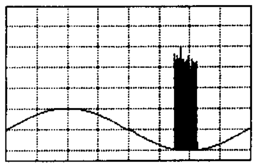
Location: SF6/air bushing mounted instead of test compartment A

Test voltage level: 45 kV

VHF-method (preampl. +57 dB) Ref. 71 mV BW 5 MHz

Conventional PD method Background noise: < 1.5 pC Ref. 12 pC/div.





f_c = 40 MHz q ~ 60 pC

Remark: only little influence of SF6/air bushing without defect on background noise level