Sensitivity Evaluation of Different Types of PD Sensors for UHF-PD-Measurements

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Abstract — **Ultra high frequency (UHF) partial discharge detection is a common on-site insulation diagnosis technique for gas-insulated switchgear (GIS) that has increasingly acquired importance in recent years. Compared to other methods of partial discharge (PD) measurement, it is less susceptible to disturbances from outside the system. It does have the disadvantage that the measured amplitude depends on a variety of different factors which make it impossible to perform a signal calibration as it is done for PD measurements according to IEC 60270. It is possible, however, to perform the so called sensitivity verification. This contribution describes the measurement and evaluation of the influence of different parameters like the type of sensor and the evaluation parameters. PD sensors were developed to have a flat frequency response up to and beyond 2 GHz which has been verified by laboratory experiments. In addition to purpose-built PD sensors, it is possible to use other components in the GIS for sensing UHF partial discharges. This is namely the earthing switch shield which is provided in all fast acting and maintenance earthing switches. The presented frequency response and the sensitivity check of these sensors prove the suitability for PD diagnostic and monitoring in almost the same manner compared to the PD sensors.**

Keywords -- UHF, PD-Measurement, Sensors, Sensitivity

I. INTRODUCTION

The demand for reliable and economic medium- and high-voltage installations is increasing due to the present rapidly changing conditions in the power substation and distribution markets. As a result, the diagnostics of gas-insulated switchgear has also generally acquired importance.

In order to perform diagnosis or monitoring of PD which occur inside a GIS, the UHF method is generally applied. Its advantage in comparison to the "electrical" measurement method described in IEC 60270 is that a bulky coupling capacitance is not required. It is however difficult to use the amplitudes of the measured signals for the interpretation of the measurement results – they are dependent on the type of defect, the architecture of the system and the distance between the defect and the measuring sensor. The same defect at a different position leads to a different PD amplitude, a calibration of an UHF PD measurement is therefore not possible. It is possible, however, to perform a sensitivity verification test that is described in the report of the CIGRÉ Task Force 15/33.03.05 [1]. The investigations which are described in this paper focus on the first part of the suggested sensitivity verification, the determination of the voltage amplitude of the pulse, which has to be injected in order to simulate a 5 pC defect (hopping particle) in the GIS.

One of the essential parameters which do have a significant impact on the results of such a sensitivity verification test is the type of sensor that is connected to the measuring system. In this paper, the sensitivity of isolated electrodes in disconnector and earthing switches is compared to the sensitivity of standard partial discharge sensors. Also, different methods for the comparison of the obtained results in respect to their frequency spectrum are evaluated.

II. INTERNAL SENSORS

ABB utilizes specially designed electric field sensors (hereafter referred to simply as 'PD sensor') for detecting PD in GIS (Figure 1). The PD sensor consists of a small modular unit which fits into earthing switch flanges of GIS components and is designed to pick up the very fast transient radio frequency pulses produced by PD.

The sensor consists of metal flange plate which house an inner sensing element supported in a coaxial arrangement by insulating material. The components are designed so as to minimize reflections and other unwanted effects, thus improving sensitivity in the UHF frequency range. The high-voltage capacitance is between the inner conductor of the GIS and the sensing element, while the stray capacitance is between the sensing element and the GIS enclosure. Measurement equipment is connected to the sensor via a standard type N-connector.

Figure 1 Photo of UHF PD sensor

The PD sensor is available for all types of ABB GIS from 170 kV to 1100 kV and was developed to have a flat frequency response up to and beyond 2 GHz which has been verified by laboratory experiments [2].
In addition to the purpose-built PD sensor, it is possible to use other components inside the GIS for sensing UHF PD, although since these are not optimized for this function [3]. This includes the earthing switch field shields. Earthing switch field shields are provided in all combined disconnector / earthing switches (DES) and fast-acting earthing switches (FAES), as shown in Figure 2.

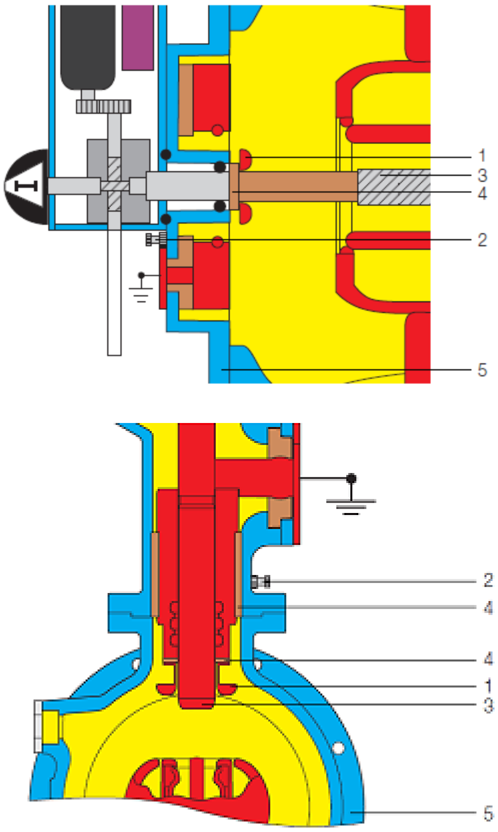

Figure 2 Drawing of the earthing switch shield in the disconnector /earthing switch (DES, above) and of the earthing switch shield in the fast-acting earthing switch (FAES, below): 1 Earthing switch shield, 2 N-connector, 3 Moving contact, 4 Insulation, 5 GIS enclosure

Originally, these earthing shields have not been designed for the sole purpose of PD measurement but also for zero potential measurement. Because of the increasing importance of PD diagnostic and monitoring also the field shields were optimized to realize a good signal-to-noise performance and sensitivity. Based on physical limitations it is not possible to reach the same flat response over the whole frequency range compared to the PD sensor. Figure 3 shows the frequency respond of the different sensors. Both the DES and the FAES sensor have a widely flat frequency response, with narrow band sections with lower sensitivity between 1.1 GHz and 1.5 GHz.

Nevertheless, both the DES and the FAES sensor are suitable for on-site PD measurement during commissioning tests, service checks and for continuous PD monitoring and allow sensitive measurements in the UHF frequency range. The frequency characteristic of the sensors has to be considered during sensitivity verification and for the PD measurement, especially if narrow-band measuring systems are used.

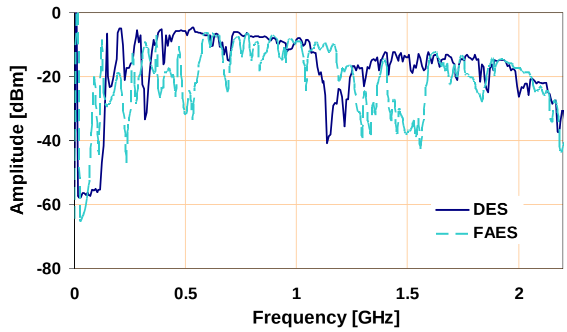

Figure 3 Sensor frequency response

III. SENSETIVITY CHECK

An apparent “disadvantage” of UHF measurements is that the UHF signal cannot be clearly correlated with the apparent charge of the PD source. In other words, a calibration according to IEC 60270 is not possible because of physical and measurement reasons. It is possible, however to perform a sensitivity verification according to report of the CIGRÉ Task Force 15/33.03.05 [1]. As a result, the GIS operator can also check the sensitivity of the UHF sensors and the measuring system according to the CIGRÉ sensitivity verification procedure on-site.

A. Comparison of Different Sensors

Figure 4 shows the test setup used for the experiments. It consists of 4 adjacent GIS compartments in which different sensors are installed. The compartments are divided by partition or support insulators. They are connected with a high voltage transformer that is equipped with a conventional PD measuring system. The complete test setup has a noise level below 2 pC. PD Sensor 2 is only used for the injection of voltage pulses. Different UHF PD measurement systems which are used in the experiments are always connected to PD sensor 1 or to the shields.
In order to compare the characteristic properties of a voltage impulse with the properties of typical defects in a GIS system, an artificial defect was placed inside the compartment which is near to PD sensor 2. As artificial defect hopping metal particles with a length of 3 mm - 5 mm and a diameter of 1 mm were used. They were placed on the encapsulation and the paint was removed in that area in order to ensure that the particles are electrically charged if a high voltage is applied to the system.
High voltage was applied to the system and was adjusted to a level where the conventionally measured PD amplitude of 5 pC was reached. UHF PD measurement systems which were

connected to the other three sensors measured the PD signal at the same time. The corresponding voltage impulse was determined by comparison of the measured UHF PD signals with the recorded signals of the voltage impulses which were injected in sensor 2. A commercially available "GIS calibrator" which was able to produce voltage steps with different amplitudes was used as source for the pulses. The origins of the PD signals that are caused by the defect and by the injected voltage pulse were very close to each other, so that the influence of the GIS geometry on the signal transmission was identical and can be neglected.

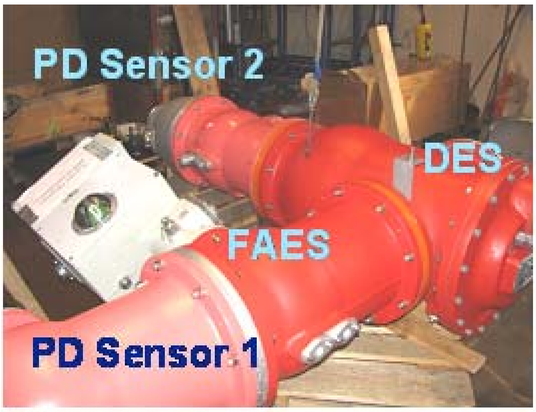

Figure 4 Picture of the experimental layout of indoor test facility (test set-up A)

The amplitude of the artificial defect was measured by a spectrum analyzer with custom made preamplifiers. A full frequency sweep in the range from 300 MHz – 2 GHz was performed. The measured spectrum consists of the maximum amplitudes which have been determined for each frequency during 60 s of measurement time. Moreover the average spectrum was also recorded. A comparison with the spectra of different voltage pulses can be done directly or with the aid of statistical tools like the measured power (MP) and the average power (AP) in the frequency spectrum, the maximum amplitude (MA) or the averaged area per data point (AR) [4]. A direct comparison of the spectra measured at the PD sensor shows that the amplitude of a corresponding voltage pulse is between 9 V and 11 V in case of a hopping particle. This result was also confirmed by measurements with a second commercial peak detection system. In case of the earthing shields the required corresponding voltage pulse is between 12 V and 13 V and therefore a little higher compared to the PD sensor.

The corresponding statistical values for all sensors are listed in TABLE I and TABLE II. TABLE I shows the results evaluated from the average spectrum, whereas TABLE II shows the values evaluated from the max-hold spectrum. The results based on the statistical values are basically in conformity with the direct comparison of the measured spectrum, especially for the average spectra (MP and AP). Of course, there are differences between the evaluation methods. Depending on the frequency response of the sensor it is important to choose the best frequency range to avoid a wrong interpretation. For the FAES sensor a frequency range from 600 MHz to 2 GHz gives a better result. Moreover, prominent peaks in the measured spectra influence the calculation results.

TABLE I STATISTICAL VALUES OF SPECTRA MEASURED AND CALCULATED FOR THE DIFFERENT SENSORS (AVERAGE SPECTRUM)

Voltage Pulse / Particle	**Parameter**			
	MP [dBm]	***AP [dBm]***	***MA [dBm]***	***AR***
PD Sensor 1				
Hopping Particle	34	5.9	18	1.6
5 V	25	-4.1	15	0.1
7.5 V	29	1.1	19	0.8
12.5 V	32	4.2	23	1.1
FAES (600 MHz – 2 GHz)				
Hopping Particle	26 (22)	-3 (-6)	11 (9)	0.23 (0.22)
5 V	27 (16)	-1.8 (-12)	19 (3)	0.05 (0.05)
7.5 V	29 (17)	0.4 (-10)	21 (3)	0.1 (0.06)
12.5 V	31 (22)	3.7 (-7)	25 (10)	0.5 (0.25)
DES				
Hopping Particle	32	3.6	19	0.7
5 V	28	-0.4	19	0.1
7.5 V	29	0.8	14	0.3
12.5 V	33	4.5	20	0.7

TABLE II STATISTICAL VALUES OF SPECTRA MEASURED AND CALCULATED FOR THE DIFFERENT SENSORS (MAXIMUM SPECTRUM)

Voltage Pulse / Particle	**Parameter**			
	MP [dBm]	***AP [dBm]***	***MA [dBm]***	***AR***
PD Sensor 1				
Hopping Particle	36	8.5	24	1.9
5 V	34	5.3	24	0.6
7.5 V	36	8.8	26	1.4
12.5 V	39	12	28	2.1
FAES (600 MHz – 2 GHz)				
Hopping Particle	34 (32)	5.4 (3.9)	23 (19)	0.6 (0.5)
5 V	35 (25)	6.8 (-3)	26 (15)	0.6 (0.2)
7.5 V	36 (28)	8.9 (-0.2)	27 (22)	0.7 (0.25)
12.5 V	39 (32)	11.6 (4)	29 (23)	1.4 (0.6)
DES				
Hopping Particle	42	14	27	3
5 V	37	8.4	23	0.9
7.5 V	39	11.4	25	1.9
12.5 V	42	15	27	3.6

B. *Influence of the Test Set-up*

In laboratory experiments, the distance of the sensor for the voltage injection and the sensor for the measurement is as short as possible. The sensors are placed in adjacent GIS compartments. In GIS installations the sensors are placed throughout the GIS according to rules based on experience and the topology of each individual installation. The distance between the sensors could reach more than 20 m. In order to determine the influence of the test set-up the results presented in chapter 3A were compared to the results using a typical laboratory test set-up for the first step of the sensitivity verification [5]. Figure 5 shows the test set-up which was used for the second test series. It consists of two adjacent GIS compartments. Sensor 1 was only used for the injection of voltage pulses. The UHF PD measurement system was always connected to sensor 2.

Figure 5 Picture of the experimental layout of indoor test facility (test set-up B)

TABLE III shows a comparison of the results for both test set-ups, based on a direct comparison of the measured frequency spectra. It could be concluded, that the effect of the test set-up and therefore, the effect of the distance between the sensors for the sensitivity verification could be neglected.

TABLE III EQUIVALENT VOLTAGE PULSE FOR HOPPING PARTICLES

	Test set-up A	**Test set-up B**
Required voltage pulse	9 V – 11 V	10 V

IV. OTHER TESTS

Beside the PD diagnostic and monitoring function, it is important to know, that the sensors as well as the connected measuring system is able to withstand the system requirements. When switching capacitive currents, the focus is on VFTO (very fast transient overvoltages) in particular. In addition to the requirements for the disconnector itself, the overvoltages that occur represent a major challenge in relation to the EMC of the measurement and control equipment [6].

As the sensor may be struck by VFTO during earth switch / disconnector operations, tests were carried out to verify that the protection mechanisms of the continuous PD monitoring systems are sufficient to prevent damage. Two system immunity tests were carried out: disconnector switching according to Annex F of IEC 62271-102 and closing operation of the earthing switch with a trapped charge voltage of 1 pu at the busbar section. The PD system was checked before, during and after each test for correct operation. The system operated correctly at all times, no failures or damage occurred during either test. The tests have shown that the PD system is suitably protected. For the FAES it is required to prove the short-circuit making performance as well as the Short-time withstand current and peak withstand current according to IEC 62271-102. The PD measuring system was connected to the sensor during these tests. Also in that case, the system operated correctly at all times. Concluding, the shield electrodes used for PD measurement are suitable for UHF PD measurements and continuous monitoring.

V. CONCLUSIONS

A partial discharge sensor is available for all types of ABB GIS from 170 kV to 1100 kV and was developed to have a flat frequency response up to and beyond 2 GHz which has been verified by laboratory experiments.

In addition to the PD sensor, it is possible to use other components inside the GIS for sensing UHF PD. This includes the earthing switch field shields. Earthing switch field shields are provided in all combined disconnector / earthing switches and fast-acting earthing switches.

During broadband measurements with the spectrum analyzer, the spectrum of the maximal and average PD amplitudes was recorded for a frequency span of 300 MHz – 2 GHz. A comparison with the measurement of the PD sensors results lead to the similar result if the equivalent voltage pulse was determined by direct comparison of the spectra.

A comparison of statistical values that were derived from the measured spectra did not lead to the same result in any case. Depending on the frequency response of the sensor it is important to choose the best frequency range to avoid a wrong interpretation. The presented frequency response and the sensitivity check of these sensors prove the suitability for PD diagnostic and monitoring in almost the same manner compared to the PD sensors.

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