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Guidelines for Unconventional Partial Discharge Measurements

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Guidelines for Unconventional Partial Discharge Measurements

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Part I
General aspects (Executive Summary)

1.1 GENERAL

PD measurement is a worldwide-accepted method for insulation diagnosis and a required part of the acceptance testing for many HV assets.
Based on the absence or presence of PD activity caused by insulation defects discharging during routine tests, on-site tests, or periodic in-service inspections throughout the service life, conclusions may be made about the actual dielectric insulation status.
To use one example, on-site partial discharge tests can be applied to prove two main characteristics of a system of HV components:

1. HV component quality and integrity of the system components
    a. As part of commissioning on-site: a check for possible damage after completed factory tests due to transportation, storage and installation.
    b. To demonstrate that the transport from the manufacturer to users site and erection on-site have not caused any new and dangerous defects in the insulation. Typically the system components are tested in the factory including the main parts and any prefabricated accessories. However the effect of transportation and the correctness of the final assembling can only be tested after completing the installation in the field.
    c. After on-site repair: to spot bad workmanship during complete installation. To demonstrate that the equipment has been successfully repaired and that all dangerous defects in the insulation have been eliminated.
2. Availability /reliability of the HV component
    a. For diagnostic purposes: to estimate actual condition of the service aged component by checking the insulation fingerprint to note any insulation degradation after a period of service operation e.g. 40 or 50 years.
    b. By providing reference values for diagnostic tools (voltage test including partial discharge) for later tests to demonstrate whether the insulation is still free from dangerous defects and that the lifetime expectation is sufficient high.

To facilitate PD measurements different techniques/methods have been developed and they are in use for laboratory and on-site applications. All these methods can be divided into conventional and unconventional PD measuring methods.
With regard to commissioning tests by the manufacturers, the IEC 60270 recommendations ‘’High Voltage Testing- Partial Discharge Measurements’’ 3rd Edition, 2000 defines the circuit, calibration and measurement-specifications. The PD measuring systems which are working in accordance to this standard are named <u>conventional PD measuring systems</u>. The use of these systems is characterized by the following:
a) test objects are energized by external voltage sources (off-line),
b) use of a specified circuit to detect the PD signals,
c) use of fixed calibration procedure,
d) measurement and display of PD magnitude in [pC] or [nC],
e) for different types of HV components acceptance levels in [pC] or [nC] are developed and used.

History shows that PD Measurement Technology has been proven as an excellent method for quality control of HV insulation for over 40 years. Due to on-going insulation aging of the HV components in service, on-site PD testing and diagnosis has attracted increased interest. Since conventional PD measuring systems used in the controlled factory environment are not always applicable for on-site, specialized PD detection and measurement methods have been introduced. These so-called unconventional PD measuring systems can detect the PD signals using different physical characteristics and the properties of the PD processes. In general, these methods are based on the measurements of:

a) electrical signals in the radio frequencies (RF) ranges e.g. HF, VHF, UHF, etc
b) light emission (optical methods),
c) acoustic waves (acoustic method)
d) PD by-products (chemical method).

Many technical studies and papers have demonstrated that there is normally NO correlation between the conventional measured and standardized apparent charge [pC] values recorded and the output values recorded by unconventional measurements. This is especially true of the RF method. Measurements using RF techniques are based on the detection of electromagnetic waves emitted by the PD event have no correlation to standardized PD measurements because the PD level recorded depends on the type of PD, the location, the sensor type and the size of the physical compartment in which the electromagnetic wave is measured. In particular, the measured values of PD signal strongly depend on the insulation defect's type and geometry and on the location of the sensor.
Since it is impossible to measure a PD event directly, remote sensors will always record values that are influenced by the fact that the PD pulse propagates some distance from the origin. The following effects are normal:

a) the loss of information about the discharge process itself with increasing distance from PD origin;
b) the increasing impact of pulse propagation path on PD waveform i.e.: reduced rise time and increased pulse width;
c) the superposition between different signals, e.g. multiple PD source, crosstalk, external interferences;

Due to the fact that there is a general interest in the application of these "non standard" methods because of their advantages for use in the field, this guide has been prepared to give recommendations for implementing them. This guide discusses the current state of the art in the field of PD measurements with non-conventional methods. Included in the following guide the reader will find actual results obtained for different types of HV components and good practice solutions are discussed.

1.2 UNCONVENTIONAL PD DETECTION

There are several methods of on-site ac voltage generation which can be applied for withstand testing and for voltage testing in combination with PD measurements. Enhanced ac voltage testing up to e.g. $1.7U_0$ or even $2.5U_0$ of defect-free /non-aged insulation does not have destructive influence on the service life of the component. Due to possibility of service lifetime consumption of installed HV circuits when over-voltage tested on-site (for after-repair or diagnostics purposes) lower ac over-voltages e.g., $0.8U_0$ should be used. Enhanced ac voltage testing higher than $1.0U_0$ of defective/aged insulation may have destructive influence on the service life of the component in service, even if no breakdown has occurred. Therefore combining ac voltage on-site testing with PD detection provides information about discharging insulation defects. Moreover it can be assessed whether the on-site test had a destructive impact on the insulation system.
It is also known that there is no general relationship between the PD intensity and the breakdown probability. Therefore PD measurement is an indirect method

which delivers indications on the extent of degradation and the danger posed by the related weak points.
Conventional PD measurement (IEC 60270) uses the apparent charge (measured in pC), which is the integrated current pulse, caused by a PD, flowing through the test circuit. The conventional method allows a precise calibration, and requires a sufficient signal-to-noise ratio of the measurement circuit to easily discern the PD in question. The standardized method of IEC-60270 and AC test protocol is well established for factory and laboratory testing, but is often not appropriate for on-site testing. In the case of field-testing where very high background noise levels are present, non-conventional methods with high signal to noise ratio capabilities are the best way to obtain meaningful measurements.

Several non-conventional PD detection methods based on acoustic and electromagnetic phenomenon have been used for some time for PD detection on power cables, transformers, GIS and generators. Up to now there have not been accepted procedures and guidelines for "non-conventional methods" compared to conventional methods. There are many open questions including: calibration or sensitivity verification procedures, techniques for noise suppression, methods of fault location, and energy equivalency, among others. The authors of this guide believe that now is the time to prepare guidelines and international recommendations for these non-conventional PD detection methods in order to ensure reproducible and comparative PD measurements on high voltage equipment between users.

1.2.1 UHF Partial Discharge Detection

Over the last decade, the UHF (Ultra High Frequency) PD method started to be successfully applied for continuous monitoring of GIS systems and to diagnose defects. More recently the application of UHF PD measurements was extended to power transformers. Partial discharge impulses in SF_6 substations are of very short rise time (below one nanosecond), so the spectrum of the high frequency electromagnetic wave contains frequencies up to 3 GHz. In coaxial GIS/GIL structures this impulse excites transient waves. The resulting PD signals propagate not only in the basic mode (TEM) but also in many higher order modes (TE and TM).

The weakly absorbed TEM waves generated by defects can propagate together with external disturbances along the GIS substation. Above a critical frequency, the partial discharge signals spread as TM and TE waves. These propagation modes can traverse gaps in the high voltage conductor but are subject to stronger absorption/attenuation. UHF PD signals are usually detected by means of various designs of field sensors that become an integral part of the apparatus.

1.2.2 HF/VHF Partial Discharge Detection

Partial discharges in polymeric insulations show a duration of several nanoseconds at the point of origin. For theoretical examinations they are often simulated with a fast exponential rise followed by an exponential decay. A transformation of the time domain signals into the frequency domain shows a constant amplitude curve of the PD frequency spectrum up to an upper frequency limit of about 100 MHz. For the measurements of PD in these types of installations, inductive and/or capacitive sensors are used. Considering as an example inductive PD measurements, a time varying magnetic field is inductively coupled with a suitable coil. For the case of a toroid coil of wire surrounding a conductor with current flow, a voltage proportional to the rapid time varying current is induced. The advantage of magnetic couplers is their galvanic isolation from the high voltage circuit. When multiple magnetic couplers are installed, systems can be connected that will measure and provide location information.

1.2.3 Acoustic Partial Discharge Detection

The acoustic partial discharge method is based on the measurement of the acoustic waves (mechanical waves) generated by the PD activity. The resulting measured signal will depend on the PD source and on the propagation path. Different acoustic modes of propagation may exist: longitudinal or transversal waves. Acoustics signals can be picked up by means of internally or externally mounted sensors. Normally, either accelerometers or acoustic emission sensors are used for these systems.

1.3 OPEN QUESTIONS

This guide is based on the current situation in the field on-site PD diagnosis with non-conventional methods as of the publication date. Several relevant problems and questions remain to be discussed and answered:

1. Concerning the types of external sensors applicable:
    a. *What are the systematic experiences using various sensors to detect the most important discharging processes e.g. treeing or tracking inside the HV component?*
    b. *At which position(s) on or in the test object should sensors be installed and what is the minimum number of sensors required to detect these potentially damaging processes in typical HV components?*
2. Conventional PD measuring systems are designed in accordance to specifications given in IEC 60270 recommendations. For un-conventional detection of PD signals different approaches exist, e.g. narrowband or wideband processing with different types of sensors being used.
    a. *Is it possible and desirable to define detailed specifications for non-conventional systems as it has been done for conventional ones?*
    b. *Is it sufficient and desirable to use calibration/sensitivity checks to adjust the system readings to some known or published levels?*
3. Most non-conventional electric PD systems are based on detecting the high frequency properties of the PD signal propagation. As a result, for sensitive detection of the PD signals, the higher frequency content of the PD signals must be observed in the time or frequency domain due to the fact that most HV components such as power cables or GIS are spatially distributed objects. Similarly, power transformers or stator insulation in rotating machines have complex inner structures which means that signal reflection and attenuation will occur. *Since most test objects are large complex impedances* the path between a particular discharge source and the sensor measuring can be lengthy and complex and result in signal attenuation which will be dependent on the frequencies of the PD signal.
    What kind of solutions are known that will avoid the situation that, due to signal attenuation effects, important PD processes will not be detectable and information lost?
4. Sensitivity characteristics of non-conventional PD systems can be approached from different points of view. In particular, the relation to particular degradation mechanisms is important and the relationship to signal propagation and attenuation effects inside the HV component is important.
    a. *How to combine these issues in defining a generic procedure to determine the sensitivity?*
    b. *Do we need a full model of the physical processes before such procedures can be developed?*
    c. *Is it possible, on the basis of laboratory experiences as collected for typical components and sensor types, to develop a uniform procedure?*

d. *Taking into account different types of HV components, what are the systematic experiences with regard to expected and possible sensitivities?*
e. *Referring to field application, what is the feedback on PD data ~~as~~ collected during on-site inspections and the service aged degradation of the insulation?*

5. The major purpose of calibration procedures of conventional PD systems is to scale the reading of the systems in a way that the measuring results are comparable with the results in conventional measuring systems.
   Concerning the calibration of non-conventional systems what would be the goal: create a system similar to conventional PD systems expressed in [pC] or limit it to some value of minimum sensitivity only?
6. Current practice for factory tests is for many HV components to have defined acceptance criteria for the PD inception voltage level (PDIV) and PD-magnitudes in [pC] or [nC].
   Which PD parameters (the same or other) have to be used to define these criteria for non-conventional PD measurements?
7. PD on-site measurement can be performed in two modes. The off line mode uses an external test source which may be capable of higher than normal operating voltages while the on-line mode uses the system line voltage,
   Taking into account the fact that there is no generalized direct relationship between PD discharges occurring in insulation defects and insulation failure: what are the reasons to continuously or periodically monitor the PD events, and what levels of monitoring are appropriate to gain the benefits?
8. It is known that the detection of the insulation degradation of most HV components cannot be fully covered by PD diagnosis only.
   What other diagnostics are complementary to PD diagnosis and can they also be successfully implemented during on-site testing? PD site location using time domain reflectometry principles is one example of additional diagnostic information that may complement the raw PD measurement.

1.4 SCOPE

It follows from the previous section that several open questions need systematic evaluation in order to provide a generic description of the most relevant aspects of non-conventional PD measuring methods. In particular, an overview will be given to describe:

1. Non-conventional PD detection systems (Part II)

2. Sensor types and relevant parameters to define the measurements sensitivity and accuracy (Part III)

3. Sensor type characteristics from the point of view of PD physical processes at the discharge site and the propagation effects in different insulating materials (Part IV)

4. Generic procedure proposed for a performance check for the system sensitivity of the set-up on-site, including the test object (Part V)

Part II
Un-conventional PD detection

2.1 INTRODUCTION

The reliability of electrical power supply is mainly dependent of the quality of power equipment. Therefore the early detection and location of potential failures outside and inside of this equipment is an important task [11]. Failures can be initiated by partial discharges (PD) and for this reason the presence and activity of PD are important criterions for the evaluation of the condition of insulation systems of electrical equipment. PD pulses ignite defects in insulation and cause macroscopic-physical effects, such as dielectric losses, electromagnetic transients, pressure waves, sound, light, heat and chemical reactions. For insulation condition assessment these effects are measured with different kinds of sensors and the results will give information about insulation defects. The analysis of this information will provide information about the condition of the insulation. Therefore the different PD detection methods can be regarded as an important diagnostic tool for non-destructive tests of insulation systems. Besides the conventional electrical PD detection in compliance to IEC 60270 [1], different non-conventional techniques are also used for both detection and location (Fig. 2.1). Such techniques are not only used for off-line and on-line PD diagnosis tests under on-site condition but also for quality assurance tests in laboratory.

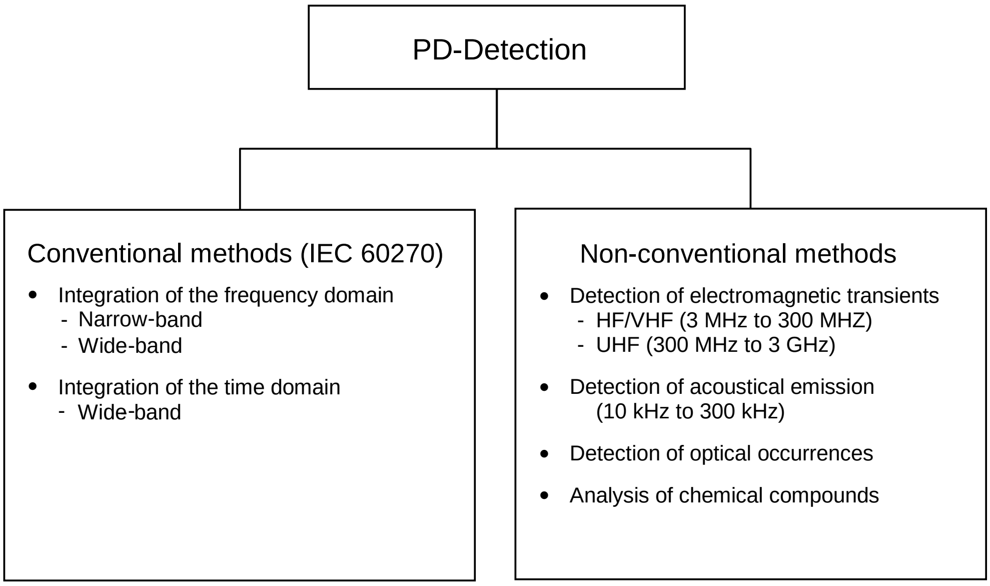


Fig. 2.1: Survey on PD detection methods in use

The main non-conventional methods used for detection and localization of PD defects are the electromagnetic (HF / VHF / UHF) and the acoustic PD detection. This part summarizes such methods, their applications, their sensitivities and their limits.

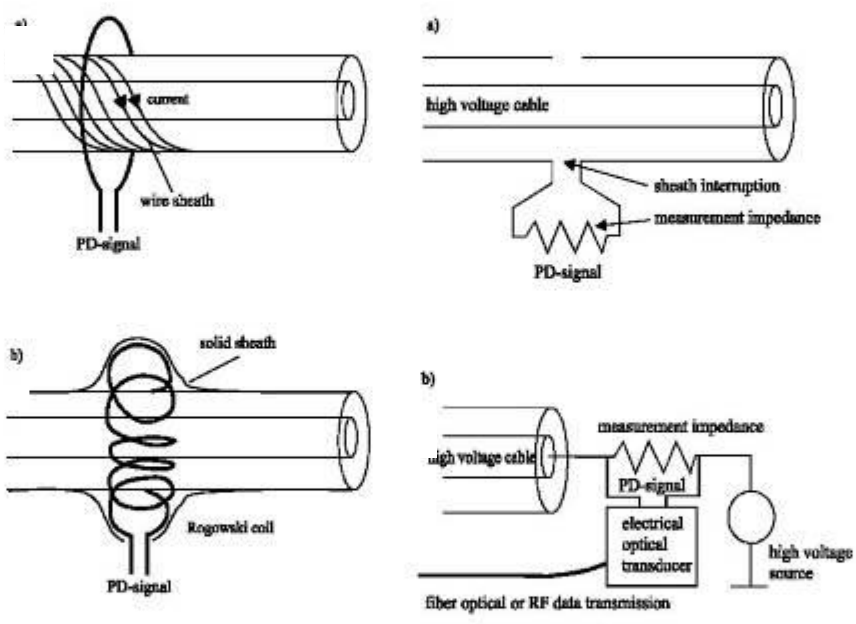
2.2 ELECTROMAGNETIC PD DETECTION

Electromagnetic PD detection methods cover the characteristic frequency ranges of HF (3 MHz -30 MHz), VHF (30 MHz - 300 MHz) and UHF (300 MHz - 3000 MHz). The PD detection in the HF / VHF range is mainly applied for power cable accessories where the electromagnetic transients are captured by means of inductive and capacitive sensors as well as by specially designed field probes. Recently, for power transformers, VHF and UHF ranges are used to decouple electromagnetic PD signals with these sensors [2], [3], [4], [5]. Table 2.1 shows the applicability of certain frequency ranges for the main components in the electrical network.

	Cables	Transformers	GIS	Generators
HF	**+**	**-**	**-**	**+**
VHF	**+/-**	**+**	**+**	**+**
UHF	**+/-**	**+**	**+**	**-**

Tab. 1: Most suitable frequency band for on-line PD detection in different components

Examples for the sensors and field probes used for power cable accessories are metallic coatings, film electrodes shielding interrupt sensors, axial field sensors, Rogowski coils and directional coupler sensors (Fig. 2.2a).



a)

b)

Fig. 2.2: a) Examples of different PD sensors
b) Rogowski coil, bandwidth 5 MHz – 100 MHz

For inductive field coupling mainly Rogowski coils are used, which cover a bandwidth from 1 MHz to 100 MHz, i.e. the HF and VHF range. These are used for both off-line and on-line PD detection (Fig. 2.2 b). Usually an equivalent sensitivity between 10 pC to 20 pC can be achieved. Furthermore, this sensor type can also be calibrated using a conventional PD calibrator.

Yoke-coils also use the inductive coupling mode and are designed for a bandwidth from 2 MHz to 50 MHz, which relates to the HF and VHF ranges. For HV bushings, an equivalent PD detection sensitivity around 10 pC can be achieved where the calibration is done by feeding the calibration pulses into the insulated bushing. If this sensor type is applied for power cables the geometric proportions, with their specific properties (damping, phase constants, propagation constants) as well as discontinuities along the cable (connection bushings, change in the profile, refraction and reflection) have to be taken into consideration. The applied sensor design as well as the geometric arrangement and the mechanical assembly of equipment are critical for determining the sensitivity and the accuracy. According to practical experience, for yoke coils an equivalent PD detection sensitivity below 1 pC can be reached, even under heavy ambient noise.

For capacitive field coupling, so-called film electrodes are mainly used which cover a bandwidth from 1 MHz to 50 MHz, i.e. the HF and VHF range. Practical experiences reveal that an equivalent PD detection sensitivity down to 1 pC can be achieved for insulated bushings and about 10 pC for adjacent bushings. This sensor type can also be calibrated by feeding a calibration pulse into the bushing.

Directional coupler sensors are based on the capacitive and the inductive principle using a bandwidth from about 2 MHz to 500 MHz, i.e. the complete HF, VHF and UHF range is covered. This advanced technology has well been proven for power cable accessories, where an equivalent PD detection sensitivity below 1 pC can be achieved even if the ambient noise level is much higher. A sensitivity check can be performed for each sensor pair, where one sensor is used as a source and the second one as a receiver.

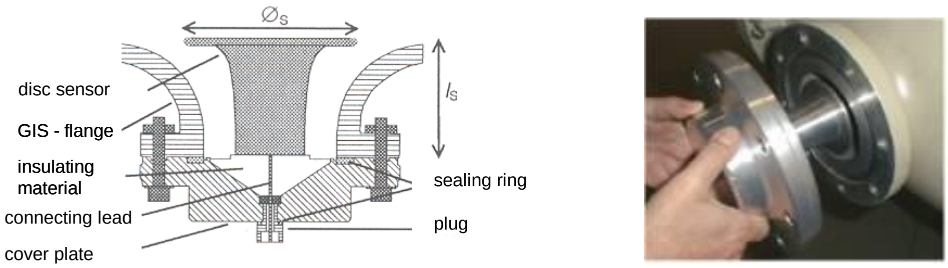


Fig. 2.3: Sectional view and mounting of an UHF PD disk sensor

If only the UHF range of PD events must be evaluated, i.e. frequencies above 300 MHz and up to 3 GHz, special designed capacitive sensors (antennas) are used, which have been proven in the past for GIS and recently also for transformers. Two types of UHF PD detection methods can be termed, the narrow band technique with a bandwidth around 5 MHz and the wide band technique using a bandwidth up to 2 GHz. In new equipment installations the UHF sensors can easily be installed (disc sensor arranged in a mounting flange). However, in existing plant, only external window sensors can be used (Fig. 2.3, 2.4). Also field-grading electrodes with their circuit equivalent as UHF loop antenna can serve for the detection of the PD signals.

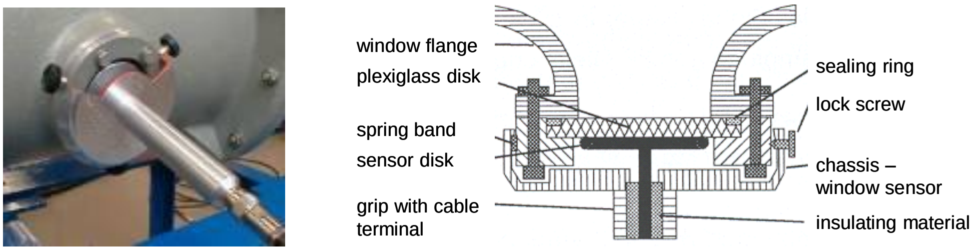


Fig. 2.4: Sectional view and mounting of an UHF PD mobile window coupler

The attenuation of PD pulses caused by the applied UHF sensors is dependent on the frequency, the geometry, the conductor material and the mode of the PD transients (TE, TEM or TM mode) [9]. Additional attenuation can also be traced back to the reflection and refraction at discontinuities. Along with the dependency of the facility configuration, the failure location and the place of the installation of the sensor, the sensitivity of this measurement is also affected by the sensor device used (Fig. 2.5). Due to the extreme high measuring frequencies this method is not disturbed by the much lower frequency spectrum of external corona discharges in air.

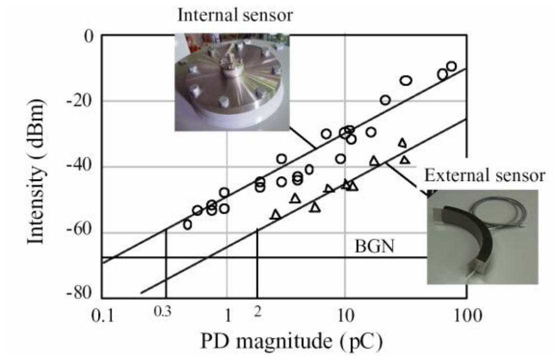


Fig. 2.5: Sensitivity of different UHF sensors

For transformer UHF PD applications, either external sensors against dielectric windows at different locations at the transformer [3], [4] or internal sensors through the oil-valve [5] (Fig. 2.6) can be applied for coupling UHF transients from inside the transformer tank. Unfortunately, the dielectric windows cannot be fitted to energized equipment in-service but rather during repair actions or in new devices. Since the sensors need no electrical connection to the high voltage circuit, the non-destructive installation of the oil-valve sensors can be managed while the transformer remains in service. In general, it can be shown that the application of four sensors results in an equivalent sensitivity of 10 pC to 20 pC and location of the PD source is possible [6, 10].

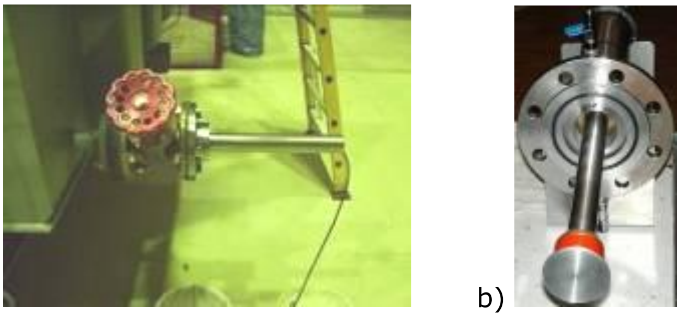
a)  b)

Fig. 2.6: a) UHF oil-valve sensor applied to a power transformer
b) Disc-shaped UHF sensor for a standardized oil-valve for online applications

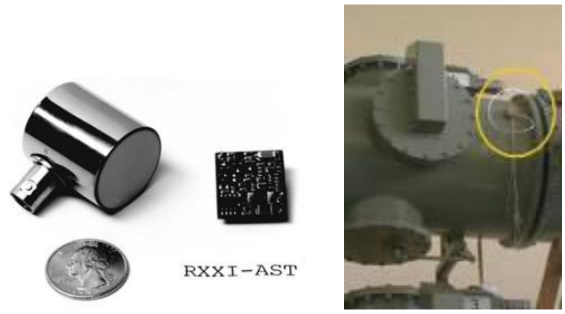
Compared to the conventional PD measuring technique, the UHF method cannot be calibrated. Therefore, a sensitivity check is used and is based upon comparative PD measurements from the laboratory and what is realized on-site [7].

2.3 ACOUSTIC PD DETECTION

Acoustic emissions caused by PD events cause mechanical vibrations and can simply be picked up by means of piezoelectric transducers as well as fiber optic acoustic sensors, accelerometers, condenser microphones and sound-resonance sensors. Because of the short duration of PD pulses the resulting compressed wave contains a frequency spectrum much above the audible sound band. The generally used frequency spectrum ranges between 10 kHz and 300 kHz. The acoustic wave propagation from the PD source to the acoustic sensor (transducer) is strongly influenced by the geometry of the test object as well as by the state of aggregation of the medium (oil, steel). Consequently, different wave types with different propagation velocities appear. In this process reflections and refractions at physical boundaries lead to distorted sound propagation that determines the resulting damping, and absorption and scattering effects on the measurable acoustic compression.

The main application for acoustic PD detection is location. Using acoustic PD detection methods primarily the PD source and respectively the point of origin is attempted to be localized. The ultrasonic PD location has been proven for high energy PD in many cases. The field of application of this method is useful for a wide range of high voltage equipment (GIS, transformers, cables etc.). Whereas the structure-borne sound of encapsulated facilities and grounded housings is captured by special designed sound sensors, such as accelerometers and piezo-electric sensors (Fig. 2.7 a), the airborne sound of outdoor facilities and overhead lines is captured by sensitive microphones (Fig. 2.7 b).

a)



b)

Fig. 2.7: a) Acoustic PD sensors for structure-borne sound
b) Ultrasonic directional microphone, frequency range 20 kHz to 100 kHz

To reach an optimum sensitivity the complete acoustic-mechanical system has to be designed and examined accordingly. Further, an influence arises as a result of the sensor size. Comparative measurements revealed, that for GIS under on-site conditions an equivalent sensitivity as low as 5 pC can be achieved (Fig. 2.8). A correlation to the PD quantity "apparent charge" measured by electrical methods cannot be expected because a calibration of the acoustic method cannot be conducted to quantify suitable reference values. For the functional check of an acoustic system, a representative wideband acoustic disturbing pulse is used.

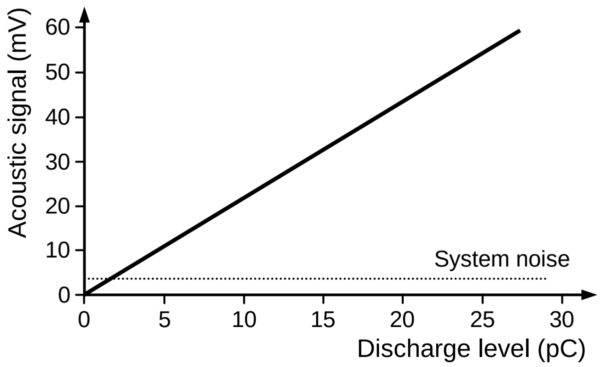


Fig. 2.8: Sensitivity of the acoustic PD detection in a 300 kV GIS

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Part III
Sensors

3.1 UHF SENSORS

Different kinds of UHF sensors are used depending on the equipment circumstances and installation. With new plant, permanently installed sensors can be built in (sensor electrode isolated from mounting flange). For older in-service equipment, external window sensors can be used, see Fig 3.1-3.12.

- Internal sensors
  - disc sensor
  - cone sensor
  - loop sensor
  - field grading sensor
- External sensors
  - window sensor (barrier)
  - pocket sensor

Internal sensors (for homogenization of the electrostatic field distribution) with their impact as UHF loop (ring) sensors can serve for detection of the PD signals, whereby investigations showed that sensitivity corresponds to those of the window sensors [1].

A comparison between internal and external sensors shows that with appropriate size e.g. of the window sensors approximately the sensitivity of a conventional UHF sensor (disc) can be achieved. With very small flange diameters, the UHF measurement is not sensitive [1].

UHF loop sensors for field installations are almost always manufactured as part of the insulation spacers. The diameter of this type of loop sensor can be nearly the diameter of GIS tank. A loop sensor is more sensitive to the TEM mode than a disc sensor [29-31] and is most effective in the VHF band.

With the simultaneous arrival of several waveforms at a sensor, different potentials on the sensor electrode can occur, so that the spatial extent of the electrode must be considered. Conventional sensors must be regarded therefore as circular disk antennas, which are characterized by their surface and gap width [1].

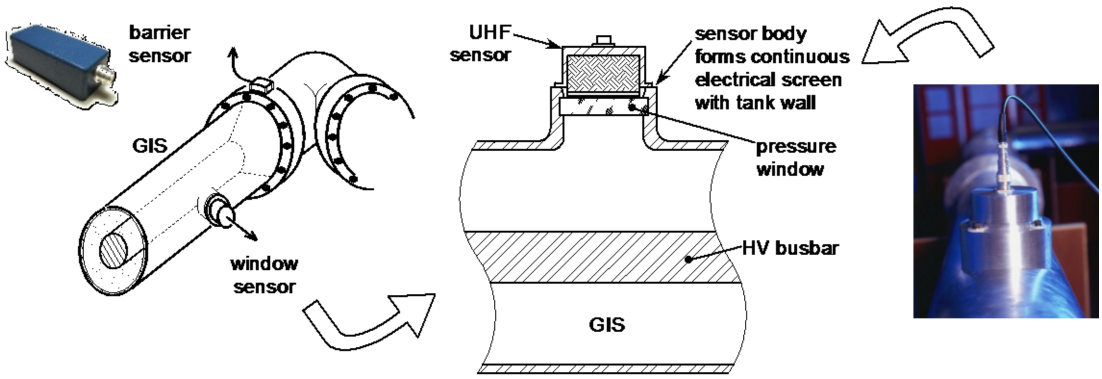


Fig. 3.1: Externally mounted barrier and window sensors for GIS [13]

Fig. 3.2: Externally mounted UHF sensor on the tank of a 1000 MVA transformer [13]

Fig. 3.3: UHF probe, mounted on the oil filling valve (DN 80) pushed inside the transformer [14]

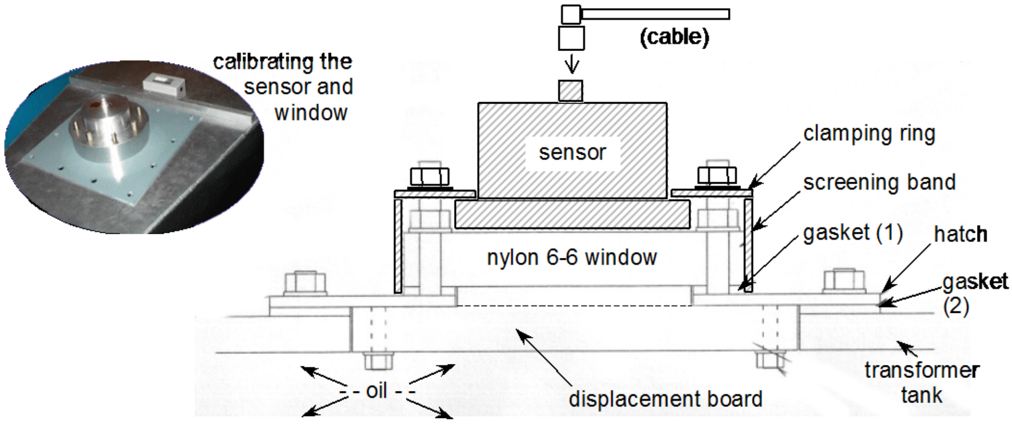


Fig. 3.4: A UHF window retrofitted to a transformer inspection hatch [13]

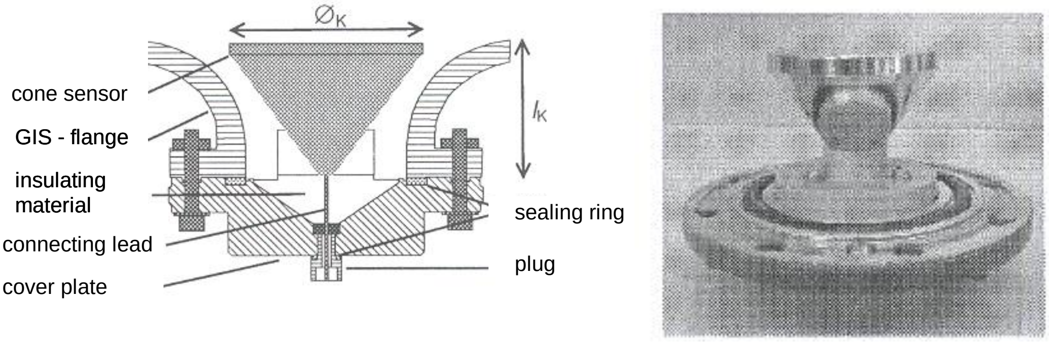


Fig. 3.5: Sectional view and mounting of an UHF PD cone sensor [1]

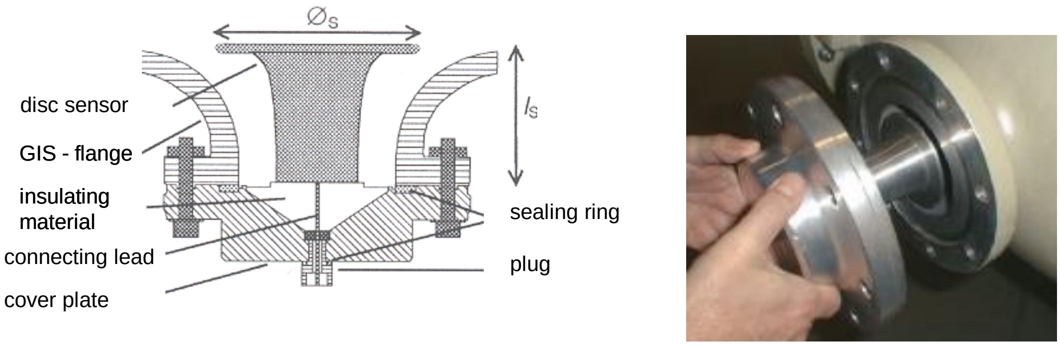


Fig. 3.6: Sectional view and mounting of an UHF PD disk sensor [1, 28]

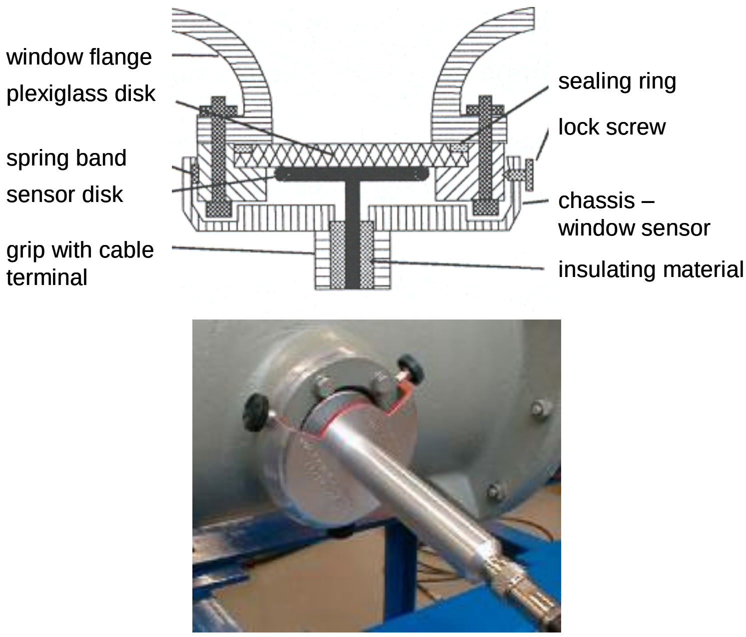


Fig. 3.7: Sectional view and mounting of an UHF PD mobile window coupler [1, 28]

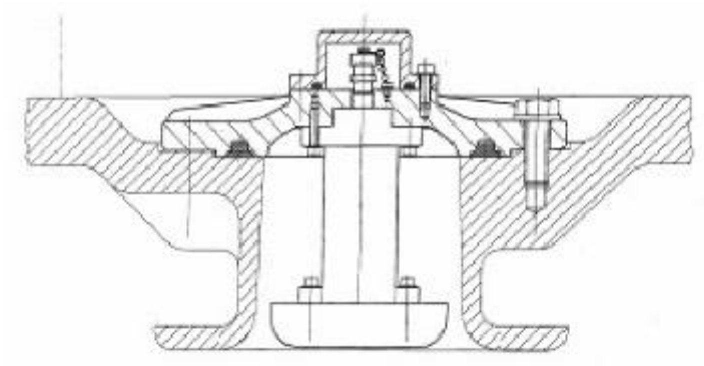


Fig. 3.8: flange sensor (ABB) [15]

	
Fig. 3.9: External window sensor with preamplifier [15]	Fig. 3.10: Different type of construction of window sensors [15]

Fig. 3.11: External ring sensor at a flange element [15]

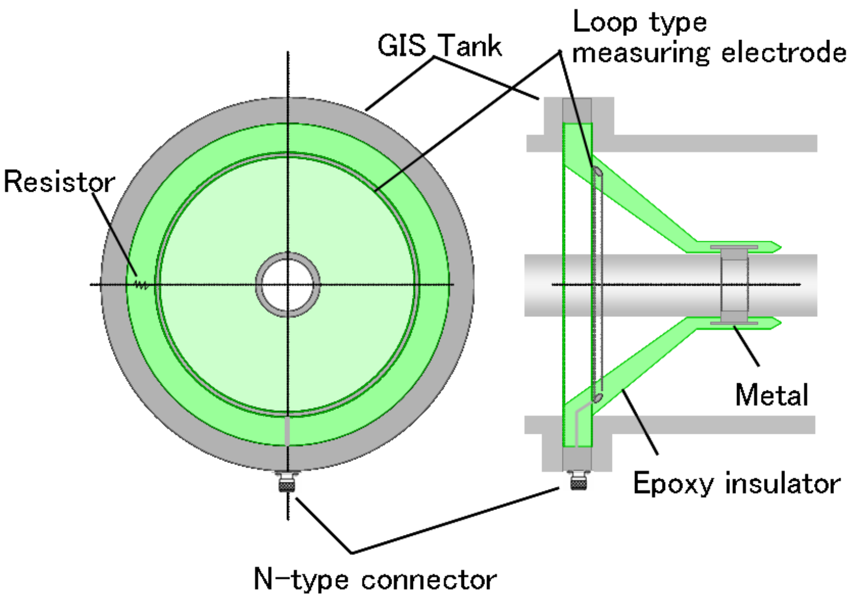


Fig. 3.12: Internal loop sensor in an insulation spacer [31]

Conditional upon the finite conductivity of the conductor material, the propagation of the electromagnetic waves is lossy. The resulting damping/attenuation is:

- Frequency dependent
- Geometry dependent

- Conductor material dependent
- Mode type (dependent)
    - 1-2 dB/km (TEM, TE-mode)
    - 4 dB/km (TM-mode)

In practice, most damping/attenuation is a result of reflection and refraction at discontinuities. This leads to very complex propagation behavior.

The intensity of the measured UHF-signals is dependent on the location of the PD-source relative to the sensor as well as the impulse rise time. Reflections at several discontinuities in the propagation path lead to the generation of electromagnetic resonances and standing waves. Damping/attenuation due to skin effect of the equipment enclosure also affects the measurement. The resulting frequency dependency of the measured PD signal is related to the HV equipment shape, and the type of sensors used [7, 8, 9].

As a basic requirement for the use of the UHF technology, the partial discharge impulses have to feature suitable time-domain behavior to be detected in this high frequency band. Therefore the main application for UHF lies in the area of gas-insulated substations where very fast PD pulses are normal. A relatively new application for the UHF measuring technique in the area of transformer monitoring. Techniques that combine UHF detection and acoustic detection also offer promise in locating defects.

3.2 HF/VHF SENSORS

This measurement method uses inductive sensors, capacitive sensors and field probes, see Fig 3.13-3.17.

- Capacitive sensors
- Inductive sensors
- Electromagnetic sensors

Metallic measuring coating, shielding interrupt sensors, axial field sensors, Rogowski coils, directional couplers, film electrodes make up the family of sensors used for this method.

Fig. 3.13: Differential Sensors [25]

Current transformer

Type	Transfer ratio at 50Ω	Primary window	Bandwidth at -3dB	Bandwidth at -6dB
CT1	1 : 10	15mm	0.5 – 80MHz	0.3 – 100MHz
CT100	1 : 10	100mm	2 – 25MHz	1.2 – 40MHz

Fig. 3.14: current transformer for PD measurement [19]

Rogowski Coil

The Rogowski coil works on the inductive principle. The frequency bandwidth lies between 1-40 MHz. Off-line, as well as on-line application is possible. The best results can be achieved off-line since the signal to noise ratio is usually better with a separate energizing source.

These sensors can be calibrated by a calibration impulse from a separate source as in conventional measurement of PD. The sensitivity typically lies between 10-20 pC [27].

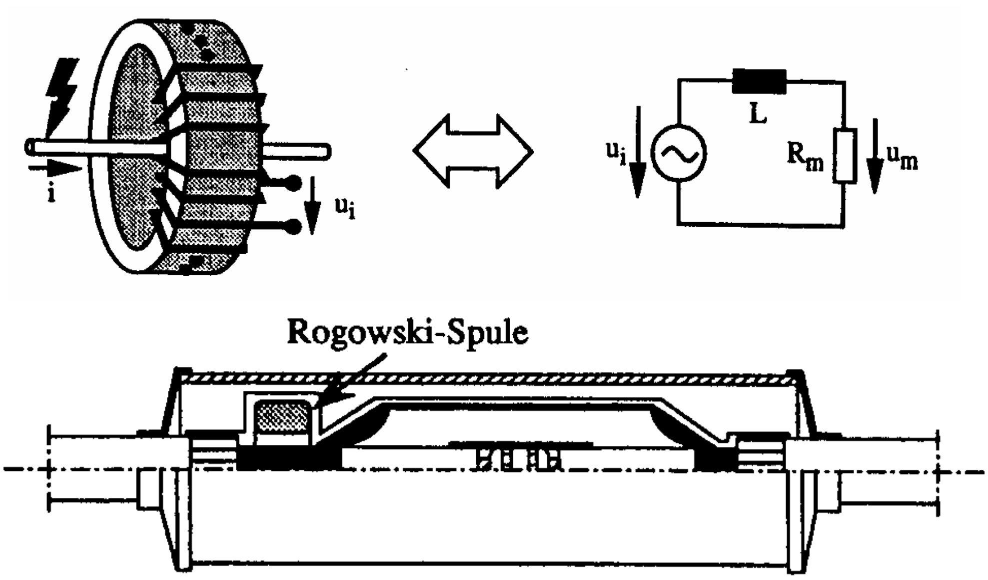


Fig. 3.15: Schematic representation of a Rogowski coil for inductive PD detection shown in a typical installation inside a cable joint and the network equivalent circuit.

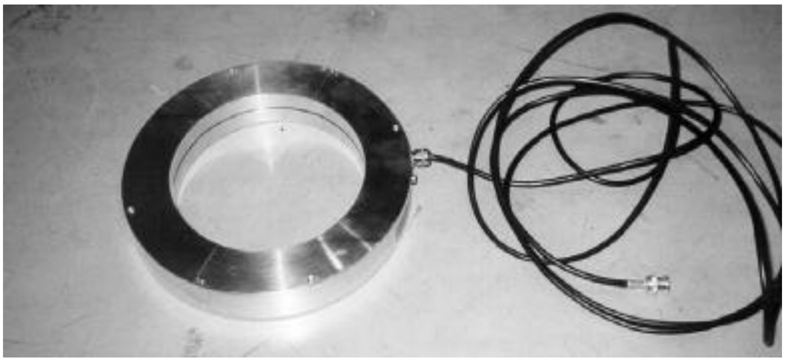
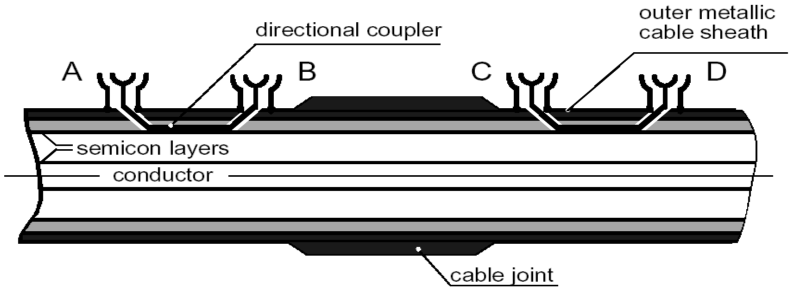
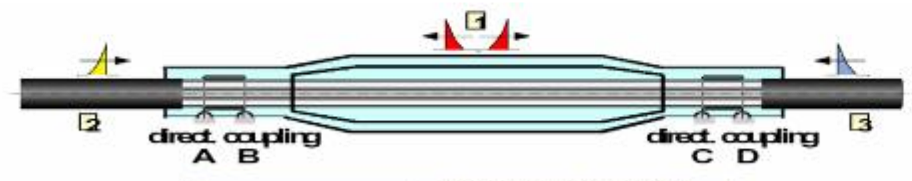


Fig. 3.16: VHF PD coupler of TE 571. Type: split ring, Rogowski coil, Ø 160mm, bandwidth 5 - 100MHz, sensitivity 96 mV/A. [20]

Directional coupler

Directional couplers work on capacitive and the inductive principles. Their frequency bandwidth lies between 2-500 MHz. Their application is for on-line as well as off-line operation. The calibration of these sensors is accomplished through the sensor itself. Every unit comprises two sensors, so for calibration one is used as source and the second as receiver. The impulse amplitude is measured. The sensitivity lies in the range of few pC [27].





impulse source / -No.	signal at coupling output A	B	C	D
joint / 1	–	X	X	–
left cable / 2	X	–	X	–
right cable / 3	–	X	–	X

Fig. 3.17: Principle of the coupler sensor and practical installation [18]

Film electrodes

This type of sensor works on the capacitive coupling principle. The typical bandwidth lies between 1-50 MHz. Off-line, as well as on-line application for capacitive couplers is possible. The calibration is conducted by a calibration impulse fed in the insulated bushing used also for signal measurement. The impulse amplitude is measured directly from the coupler. The sensitivity realized is approximately 1 pC for insulated bushings and 10 pC for adjacent bushings [27].

Yoke-Coil

This type of sensor works on the inductive coupling principle. The typical bandwidth lies between 2-50 MHz. Off-line, as well as on-line application for inductive couplers is possible. The calibration is conducted by a calibration impulse fed in the insulated bushing used for signal measurement. The impulse amplitude is measured directly from the coupler. The sensitivity realized is approximately 10 pC. This method can only be used for wire-shielded cables [27].

In the case of the application for power cables, the geometric proportions with their specific properties (damping, phase constants, propagation constants) as well as discontinuities along the cable (connection bushings, change in profile, refraction and reflection) which also influence the impulse shape all have to be considered.

The main field of application HF/VHF detection exists in the field of high voltage cables. Experience has shown that the measuring sensitivity of various sensors designed for this spectrum is sufficient to make meaningful measurements and that the location of a defect of certain magnitudes is possible. New developments show that the VHF PD measurement technique is also useful for transformers.

3.3 NON-ELECTRIC SENSORS

For acoustic measurements the following devices are used, see Fig 3.19:

- Piezo-electric sensors (sound emission sensors)
- Structure-born sound-resonance-sensors
- Accelerometers
- Condenser microphones
- Opto-acoustic sensors (in development)

The mounted structure-born sound sensors work in a range between 10 kHz up to several 100 kHz (1 MHz).

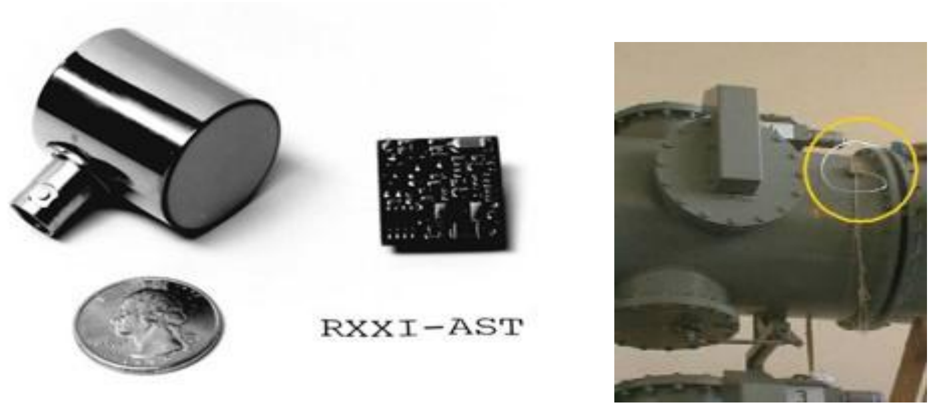


Fig. 3.18: PD acoustic sensor

Fig. 3.19: Ultrasonic measuring instrument with directional microphone:

Frequency range 20 kHz to 100 kHz

Audio-frequency range 100 Hz to 3 kHz

The field of application for acoustic PD-detection lies in the physical location of insulation defects. Two different methods can be used for the location [21, 22]. There is a possibility to determine the location by the different running times of the signals to the various sensors or the change in amplitude and deformation of the signal which is related to how far it has to travel [3].

- Amplitude and signal deformation-location
- Running time based methods

The running time based method can be separated in two methods:

- Mixed acoustic method
- Strictly acoustic method

During the mixed acoustic method the electric signal of a simultaneous conducted conventional PD method delivers the trigger command for the acoustic measurement.

The propagation of the acoustic impulse is dependent on the equipment dispersion (frequency dependant wave velocity in all-solids) and a frequency dependent damping caused by construction and insulation structures, which has a high dependency of the damping on the point of origin [1]. Furthermore the gas pressure and the encapsulation material used in GIS play a major role.

The strictly acoustic method works with sensors placed in several planned geometric locations, detecting the point of origin from the sensor positions and signal running times. The field of application for acoustic measurement of discharges spans over the large part of high voltage equipment including GIS and power transformers.

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Part IV
Signal transmission and transfer characteristics

4.1 UHF METHOD

The sensitivity of a UHF measurement is dependent on the configuration of the HV apparatus being tested, the defect location, the location of the sensor, and the type of measurement equipment. The performance of a measuring system depends on the sensor characteristics (frequency response), the measuring cable with its damping characteristics, the amplifier characteristics (dynamic noise levels) and the measuring instrument itself, see Fig 4.1-4.7.

The measuring sensitivity for UHF is found to be comparable with or even higher than conventional PD-measurement systems. It has to be considered that under most circumstances there is no direct correlation between the PD values measured in the UHF-band and the apparent charge measured by IEC 60270 compliant systems. That is to say a detection of partial discharges with the UHF-method is possible, but not the measurement of the apparent charge according to IEC 60270.

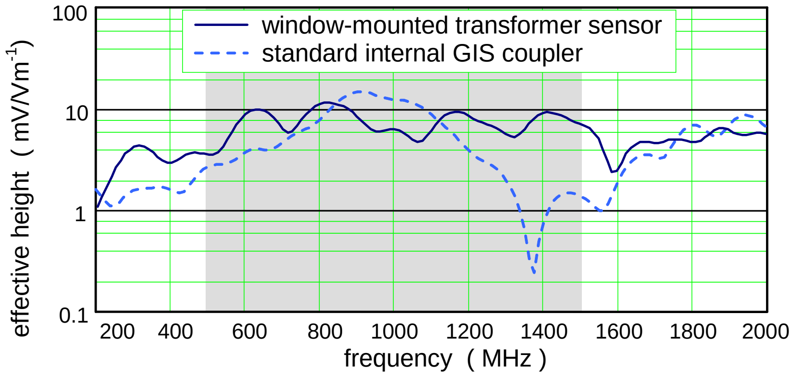


Fig. 4.1: Example of frequency response of a window-mounted sensor compared with a UHF coupler for GIS. The shaded region defines the specified operating band of 500 to 1500 MHz [13]

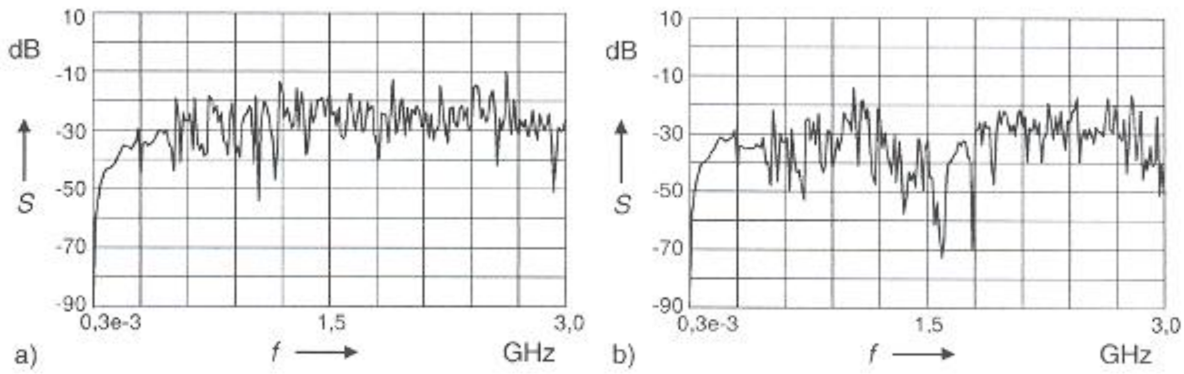


Fig. 4.2: Measured value of the transfer function of:

a) disk sensor (r= 4,5 cm, l = 8,1 cm, gap length 2,9 cm)

b) cone sensor (r= 5 cm, l = 7 cm, gap length 2,45 cm) [1]

The sensor features a nearly constant frequency response in the UHF-band (Fig. 4.3). The sensor frequency response gives an estimate of the useful UHF PD spectrum and also indicates the sensitivity of the UHF method [1].

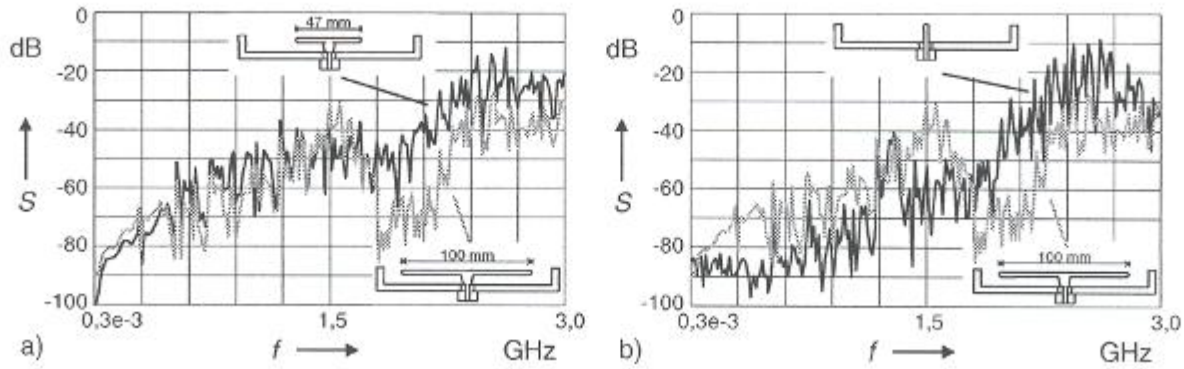


Fig. 4.3: Transfer function of a window sensor against the diameter of the sensor disk

a) Comparison 100 mm (gray) und 47 mm (black)

b) Comparison 100 mm (gray) and terminal pin (black) [1]

In the range up to 480 MHz the sensitivity increases at higher disk diameters (Fig. 4.4). Between 480 MHz and 1,8 GHz the influence of the disk diameter on the sensitivity is not significant (minimum size preferable). At very high frequencies the connecting piece has the highest sensitivity (axial field components are injected particularly well) [1].

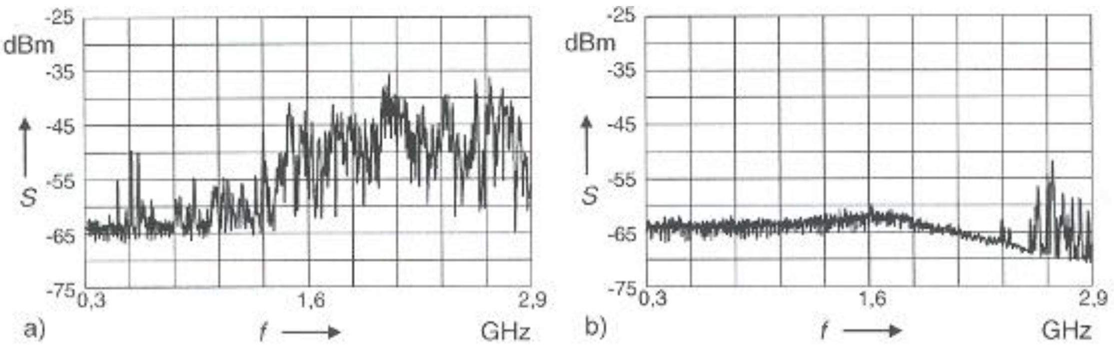


Fig. 4.4: Spectrum of a loose particle measured with a window sensor

a) Without flange extension

b) With flange extension of 10 cm [3]

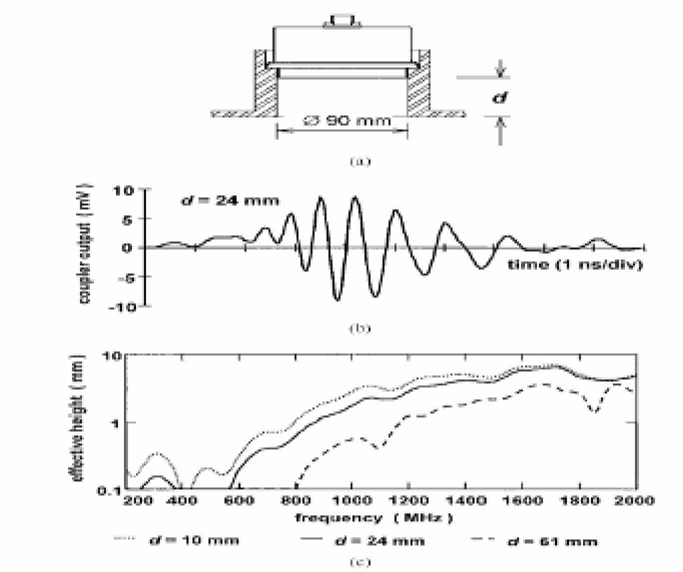


Fig. 4.5: Sensitivity of a window coupler at various window depths:

(a) mounting configuration of the coupler,

(b) step response coupler output voltage when *d* = 24 mm, and

(c) frequency response at three depths *d* [16]

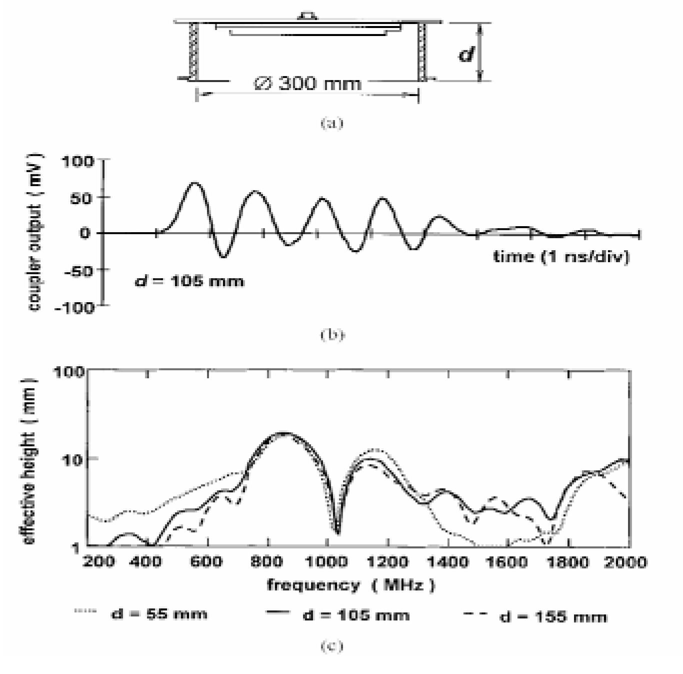


Fig. 4.6: Sensitivity of an internal coupler mounted at various depths:

(a) mounting configuration of the coupler,

(b) step response coupler output voltage when *d* = 105 mm, and

(c) frequency response at three depths *d* [16]

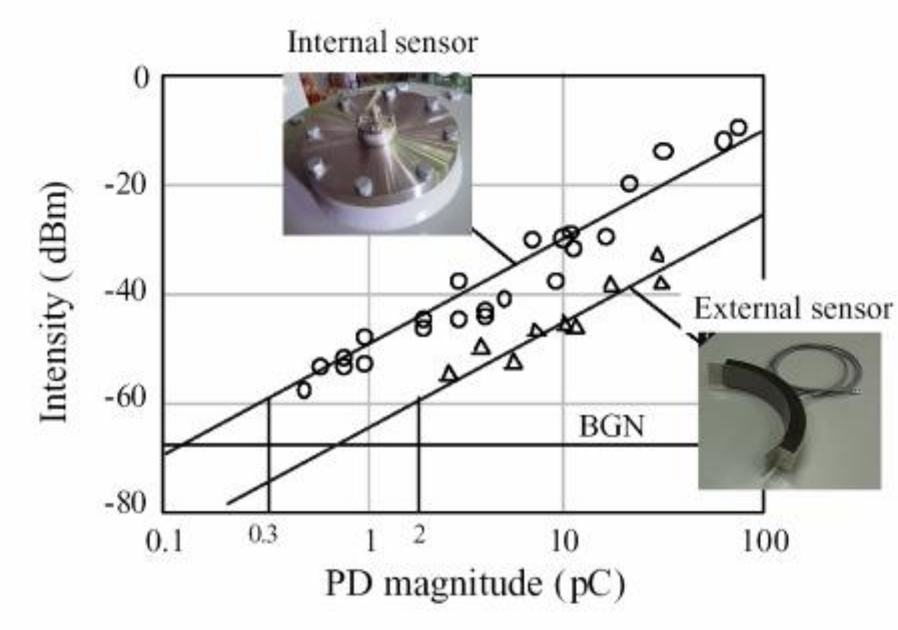
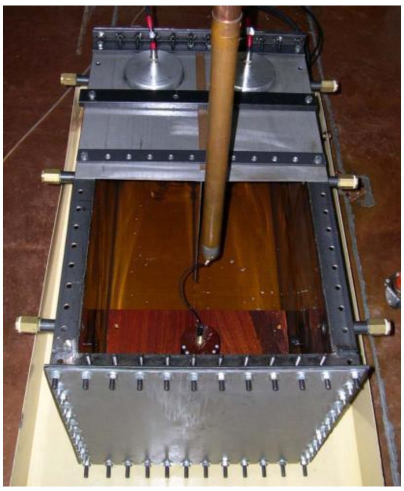


Figure 4.7: Sensitivity of developed UHF sensors [17]

4.1.1 Damping of electromagnetic signals

UHF PD signals pass through different insulation materials, like oil and paper as well as structures, for example complete windings, on their way to the measuring system. In the following example, the general influence on UHF PD signals caused by passing through the materials and structures mentioned above is represented. A goal of the investigations was less to analyze absorption than rather to find an integral statement about the influences. In experimental investigations the dominating materials and structures of oil/paper-insulated transformers were used. Specifically the arrangement included an 8.2 cm thick press board, a 0.5 cm gap in a metal plate as well as a part of a disk winding. Together with the insulating oil they represent the normal range of the materials of a transformer, which are relevant for the study of UHF PD signals. For comparison of the UHF



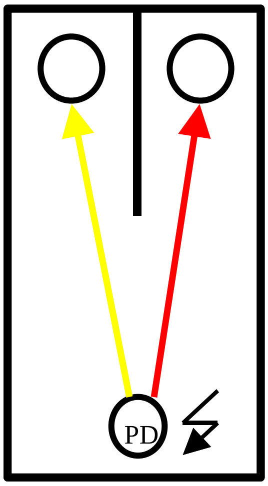


Fig. 4.8-path-arrangement, left) photo, right) schematic view

measurements, simultaneously an electrical measurement according to IEC60270 records the apparent charge value compared to the UHF signal source. The UHF

impulses were measured without amplification with a transient recorder with an analogue bandwidth of 3 GHz.
An important aspect of the experiments was the stipulation to always measure the same UHF signal with two independent disk sensors. To accomplish this test set-up shown in fig. 4.8 was developed.

The propagation paths including the disk sensors and the measuring cables had to be as similar and symmetrical as possible. This was done so the influence of a structure inserted in only one of the two propagation paths, could be analyzed directly by comparison of the two signals measured at the same time. Three comparisons were used: 1) comparison of the time signals, 2) comparison of the signal spectra and 3) comparison of the signal energy of the UHF signals.

The laboratory set-up consisted of half of a closed metallic test tank (1.0 x 0.5 x 0.5) m^3, a needle-sphere PD source, two identical disk sensors and a transient recorder. The two sensors were electromagnetically decoupled by a metal wall between them. This metal wall divided the closed half of the tank into two parts. In fig. 4.8 this so-called 2-path-arrangement is illustrated.

The objective of using this arrangement is to measure the same UHF impulse independently. Alternatively, to examine two UHF impulses of the same apparent charge would introduce a great uncertainty in the statement, since so far no clear relationship of the UHF signals with the apparent charge was found and impulses of same electrical charge may not emit the same electromagnetic signals.

Prior to the different tests with materials and structures, reference measurements were made before filling the system with oil. This reference measurement was made to show the greatest possible similarity of the theoretically identical signals. In fig. 4.9 the simultaneously measured UHF impulses of 3.7 pC are shown with their frequency spectra.

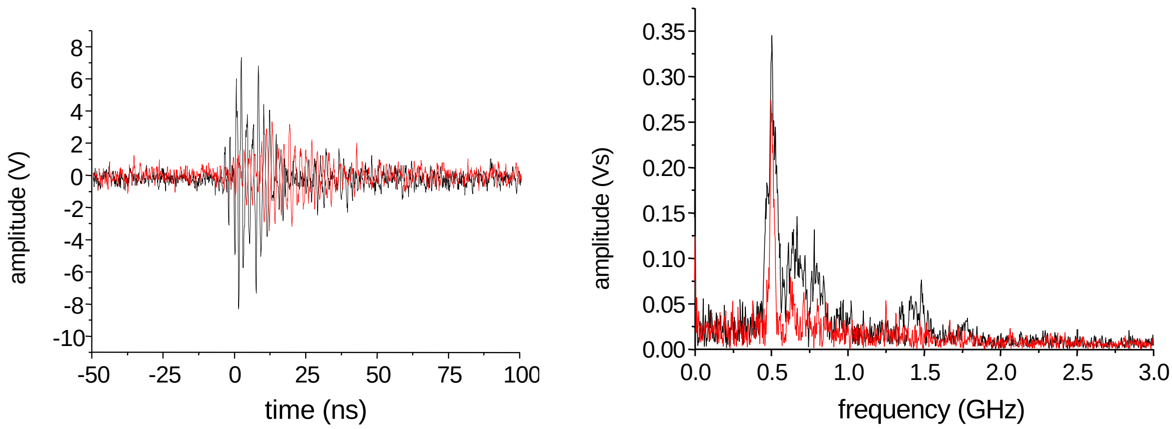


Fig. 4.9: Simultaneously measured UHF-signals of a 3,7 pC PD, left) time signal right) frequency spectrum, both signals. (Black colour in oil; read colour in air)

A good agreement between the two signals in the time and frequency range is clear; however a direct quantitative evaluation of similarity is missing. As a simple evaluation of the similarity of the signals, the signal energy of the impulses was selected as criterion. One side in the 2-path-arrangement always served as reference side and was filled with transformer oil. The measured and computed signal energies were evaluated in relation to this reference side. The

relative deviation is a quantitative value for the influence or absorption of the signal energy by the various materials and structures. In the case of the reference measurement with exclusive oil filling a relative deviation from 4,27% (-0.19 dB) with a standard deviation from 4,36% in a series of measurements from seven trials with the electrical charge level between 1,8 and 3,7 PC resulted. This standard deviation of the relative deviation can be seen as uncertainty for the following material tests. The reason for it is probably not due to the imperfect symmetry of the test arrangement, but rather due to the stochastic nature of the electromagnetic radiation of the PD source and the resulting asymmetric formation of certain resonances in the metal tank.
In fig. 4.10 the experiments with different materials and structures are illustrated.

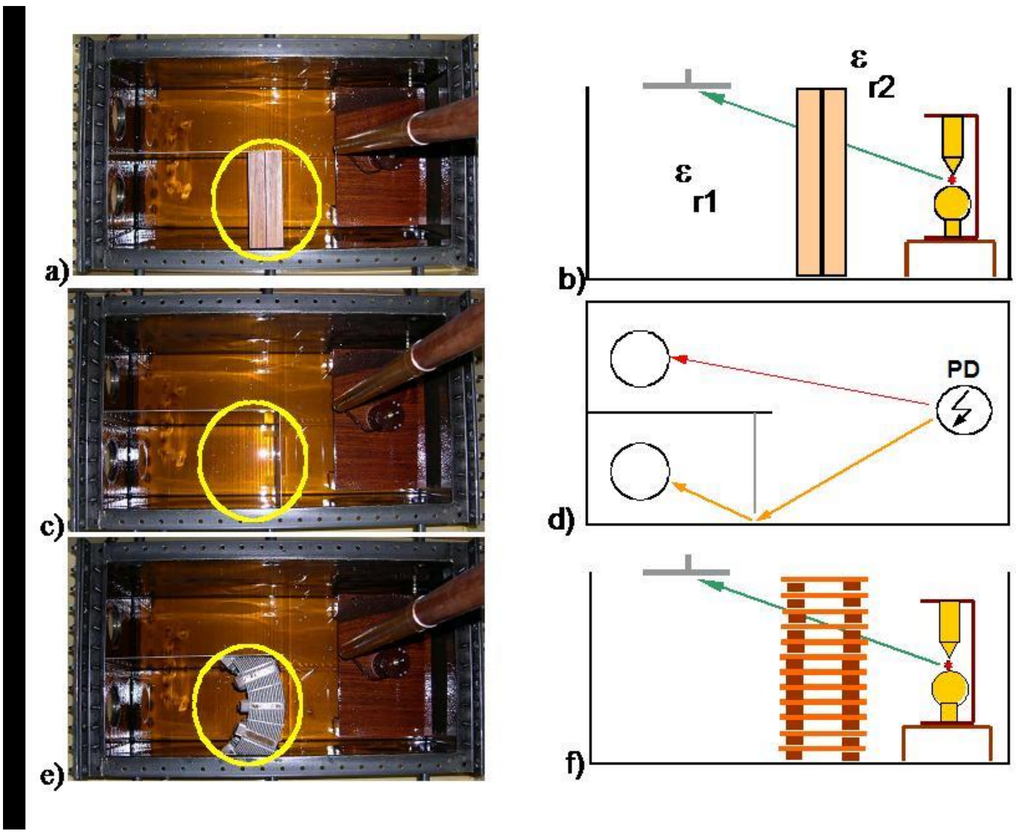


Fig. 4.10: 2-path-arrangement with different materials and structures: a) 8,4 cm press board (yellow circle); b) schematic side view of the test setup with press board; c) 0,5 cm gap in metal plate (yellow circle); d) schematic plan view of the arrangement with the propagation paths; e) Part of a disk winding (yellow circle); f) schematic side view of the test setup with the disk winding

The time signals and resulting spectra of the experiments with press board and with the disk winding exhibited a large similarity. Only a temporal shift within the range of 200 - 300 ps due to the different permittivity (ε_r) was visible. The signals, which were restricted by the 0.5 cm gap experienced a stronger influence. The temporal delay values fell between 2,9 and 5 ns. Also the spectra showed a certain degree of absorption. Concerning the absorption of the signal energies for the three experiments the following values were determined:

34,46 % (-1,83 dB) for the pressboard (thickness 8,2 cm)
Standard deviation 4,28 %
Charge level: 2,7 – 6,9 pC

46,31 % (-2,70 dB) for the 0,5 cm gap in the metal plate
Standard deviation: 8,30 %
Charge level: 2,7 – 6,9 pC

38,25 % (-2,09 dB) for the sector of a disc-winding
Standard deviation: 8,87 %
Charge level: 2,1 – 7,1 pC

Summarizing the three experiments may lead to the suggestion that electromagnetic UHF PD signals can propagate within the entire transformer with comparatively low attenuation factors. For PD occurring within windings either a propagation path in the gap between the high and low voltage winding or even through one disc winding should result in a detectable signal. In this field, due to the fact that that damping of a winding is different from sources in the vicinity of the winding and a source further away more investigation is still necessary.

4.1.2 Cavity resonances inside of power transformers

With the exception of radiated spectra, measurable UHF spectra of different PD sources inside transformers are dependent on the transfer characteristics of all the materials and structures within the propagation path of the UHF signals between the PD source and the measuring system. This includes the transfer characteristics of the sensor and the measuring cable. To accurately view the overall picture the absorptions, diffractions and reflections of the signals from windings or from the iron core must be included. The transformer tank is nearly a closed metal container and it acts as a resonator for electromagnetic signals. These cavity resonances and their characteristics can be demonstrated in laboratory conditions.

4.1.2.1 Theoretical Background

If one regards the transformer tank as three-dimensional cavity, which is formed by perfectly leading surfaces, then the following equation describes the analytically calculable cavity resonances:

$$f_{nmp} = \frac{c_0}{2\sqrt{\varepsilon_r}} \sqrt{(\frac{m}{a})^2 + (\frac{n}{b})^2 + (\frac{p}{c})^2}$$

c_0 represents the speed of light, ε_r the permittivity of oil can be approximated as 2.2, a, b and c are the geometrical dimensions of the transformer tank. For meaningful computations of the cavity resonances m, n and p should be given in whole numbers, whereby at least two have to be non-zero [1]. Resonances of larger transformer tanks lie in the order of 10 MHz. For example a tank with the dimensions (7.0 x 2.5 x 3.5) m^3 has the calculated resonant frequency of 32 MHz.

The equation above describes the resonant frequencies of empty cavities, i.e. without further leading or potential prominent parts on the inside. Investigations with laboratories as cavities show that internal structures can detune or absorb the cavity resonances [1].

4.1.2.2 Laboratory Measurement

In order to examine the occurrence of cavity resonances with UHF signals, a test tank with the dimensions (1.0 x 0.5 x 0.5) m^3 was equipped with a point plate PD source and filled with insulating oil. For measuring the electromagnetic signals a monopole with a 3 dB absorption cell was used in combination with a transient recorder with a analogue bandwidth of 3 GHz. At the same time a separate transient recorder connected to a PD measurement circuit according to IEC60270 was installed. Without amplification and with a bandwidth of 1 GHz, apparent charge levels of at least 50 PC could be detected.
Due to repeated reflections of the electromagnetic waves within the transformer tank, the duration of the measurable signals lay within the range of 1000 ns, see fig. 4.11. In the associated spectrum the analytically computed cavity resonances are illustrated [1]. The occurrence of cavity resonances could be proven with the help of the presented lab test. It is observed that the number of possible resonances increases rapidly with the increasing size of transformer tanks. The measurable resonances observed are not just cavity resonances. The observed resonances are resulting of the frequency content o f the source and the cavity resonator. PD sources in transformer may have widely different characteristics and frequency content [2].

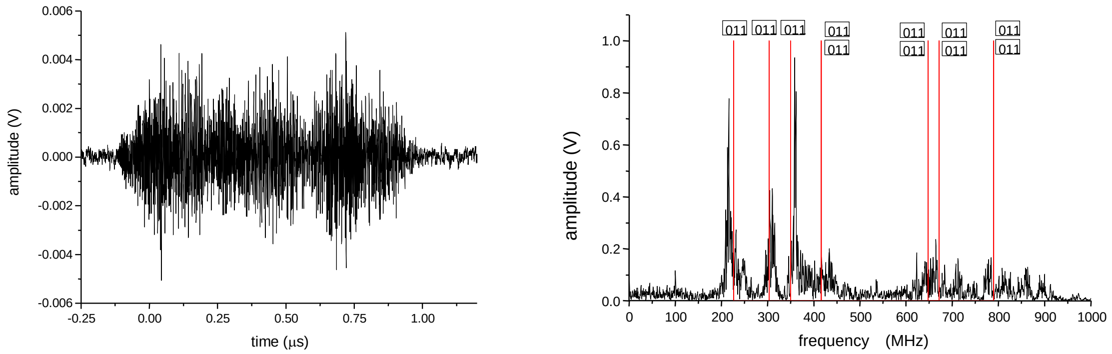


Fig. 4.11: UHF time signal and frequency spectrum (with cavity resonant frequencies) of a 285 pC PD

The knowledge about the existence of such resonances can be used advantageously for the research and development of narrow-band measurements.

4.2 HF/VHF METHOD

The applied sensor as well as the geometric arrangement and the mechanic assembly of the measuring equipment are decisive for the sensitivity and accuracy.

As an example, the application of a HF/VHF detection system to cables is used to present the signal transmission and transfer characteristics of the different parts present in the setup.

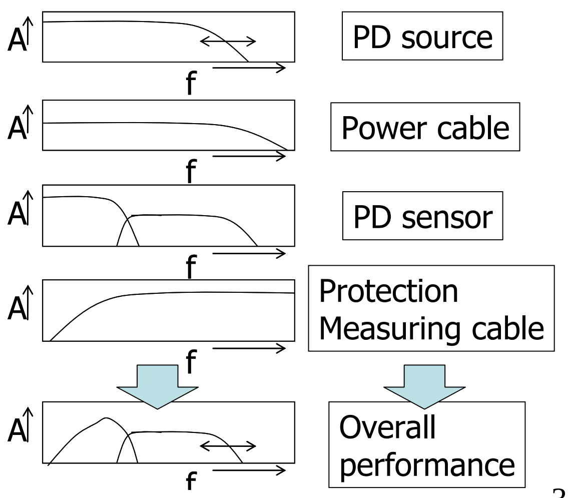


Figure 4.12: Influencing factors in overall transfer function.

Basically, the factors that influence the frequency response are:

1) The radiated frequency by the partial discharge
2) The propagation of the signals in the power cable and accessories
3) The influence of the applied sensor that couple the signals out of the cable system
4) The electric circuit and cabling between the sensor and the measuring equipment

The goal is to find the overall transfer characteristic (note here generally you evaluate a transfer function by knowing the transfer characteristics of the measuring system), from a discharging source to the measuring equipment, see figure 4.12. Knowing the frequency response of the measuring setup, frequencies which are relatively less attenuated can then be preferred to perform measurements with so that the highest possible sensitivity can be achieved.

The term transfer *function (transfer function is a mathematical evaluation—see above) of a system* will be used in the following paragraphs to describe transmission or attenuation at specific frequencies. From the above mentioned influencing factors, the radiated spectrum of the discharging source is usually not known. However, in case of power cables, a broad spectrum up to 500 MHz is known from practice. In the following paragraphs the influence of the other components are further described.

Power cable

The attenuation of a 345 kV power cable has been estimated and measured. The measurements have been performed by soldering a BNC-plug to the conductor of the power cable, as can be seen in figure 4.13a. The results of the measurement and calculation are shown in figure 4.13b.

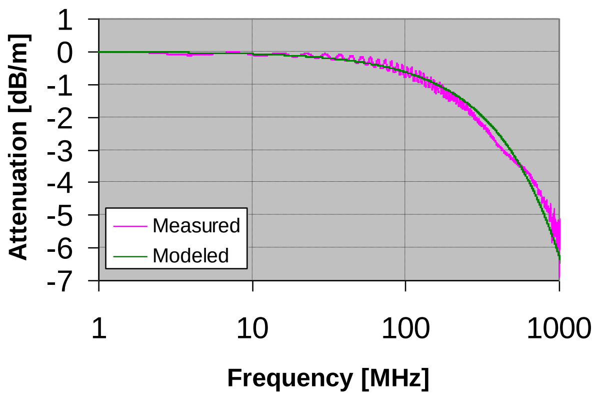


Figure 4.13: a) 345 kV cable with BNC-connector and b) measured (pink line) and modeled (green line) HF attenuation a 345 kV XLPE insulated power cables

From figure 4.13b can be concluded that PD signals propagating through a power cable are highly attenuated, especially in the VHF and UHF regions of the spectrum. Because of this high attenuation it would be difficult to see any discharge signals beyond several meters from an actual discharge site. This makes the VHF technique very suitable for after laying testing of new power cables if sensors are installed in accessories, because the accessories are known to be the most likely parts to have defects in newly installed power cable systems.

Cable Terminations

A cable termination is designed to terminate an XLPE insulated high-voltage cable in outdoor conditions. The self-inductance of a cable termination with a height of 4 m is approximately 4 μH and can therefore be modeled by a single inductance. Figure 4.14 shows the complete test system.

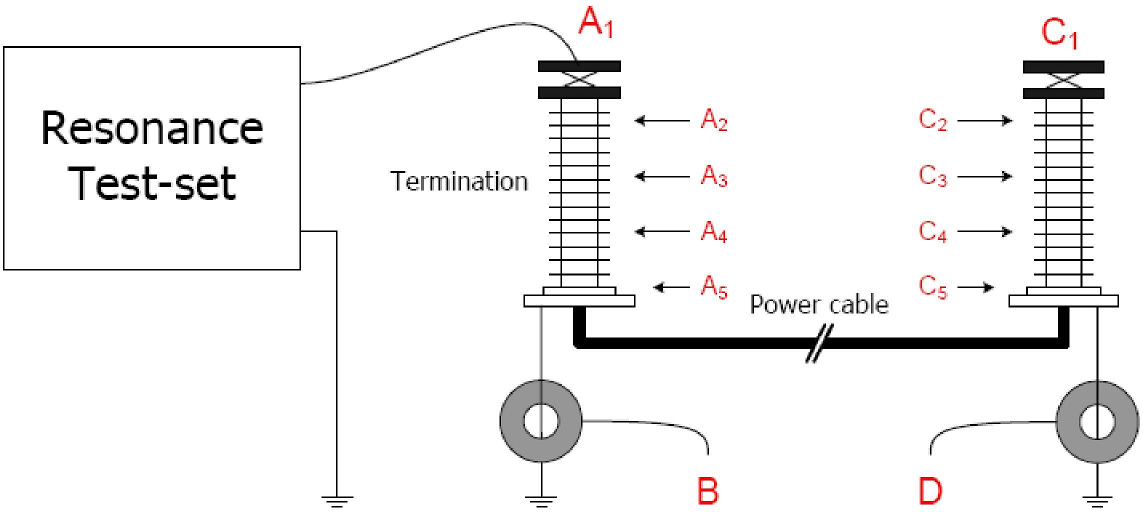
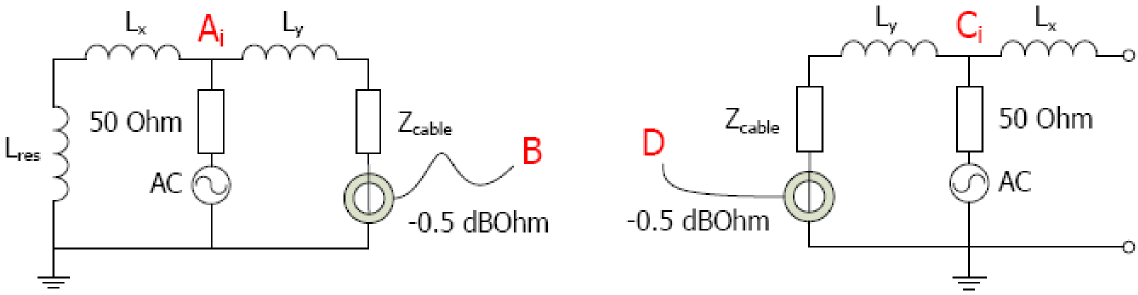


Figure 4.14: The HV system to be modeled

The HV system can be modeled into an equivalent circuit as shown in figure 4.15. The inductance of the termination is split into two parts ($L_x + L_y = 4$ μH) depending on the assumed PD location. Two separate models are used because the two sides cannot 'see' each other because of the high attenuation of the power cable, which is assumed to have a significant length.



(a) (b)

Figure 4.15: Models used for calculations: (a) Model of the left side of figure 4.14, and (b) Model of the right side of figure 4.14

To simulate a signal injection in A_i and C_i, the values of the two inductances L_x and L_y, together forming the total self-inductance of the cable termination, have been varied. This is done as follows:

- A_1 to B and C_1 to D: L_x = 0 μH, L_y = 4 μH (dark-blue)
- A_2 to B and C_2 to D: L_x = 1 μH, L_y = 3 μH (pink)
- A_3 to B and C_3 to D: L_x = 2 μH, L_y = 2 μH (yellow)
- A_4 to B and C_4 to D: L_x = 3 μH, L_y = 1 μH (turquoise)
- A_5 to B and C_5 to D: L_x = 4 μH, L_y = 0 μH (violet)

The transfer function (TF) at different frequencies was then calculated for the various cases by using the input at A_i or C_i a signal with constant amplitude at all frequencies in the bandwidth of interest. From the calculations it was seen that the presence of the resonance test system (high impedance source) has no influence on the final TF therefore the TFs from A_i to B and from C_i to D were identical. The final results are shown in figure 4.16. The calculations show that the differences at the TFs are increasing with frequency resulting at a maximum difference of 35 dB at 500 MHz between the TFs of A_1 to B and A_5 to B.

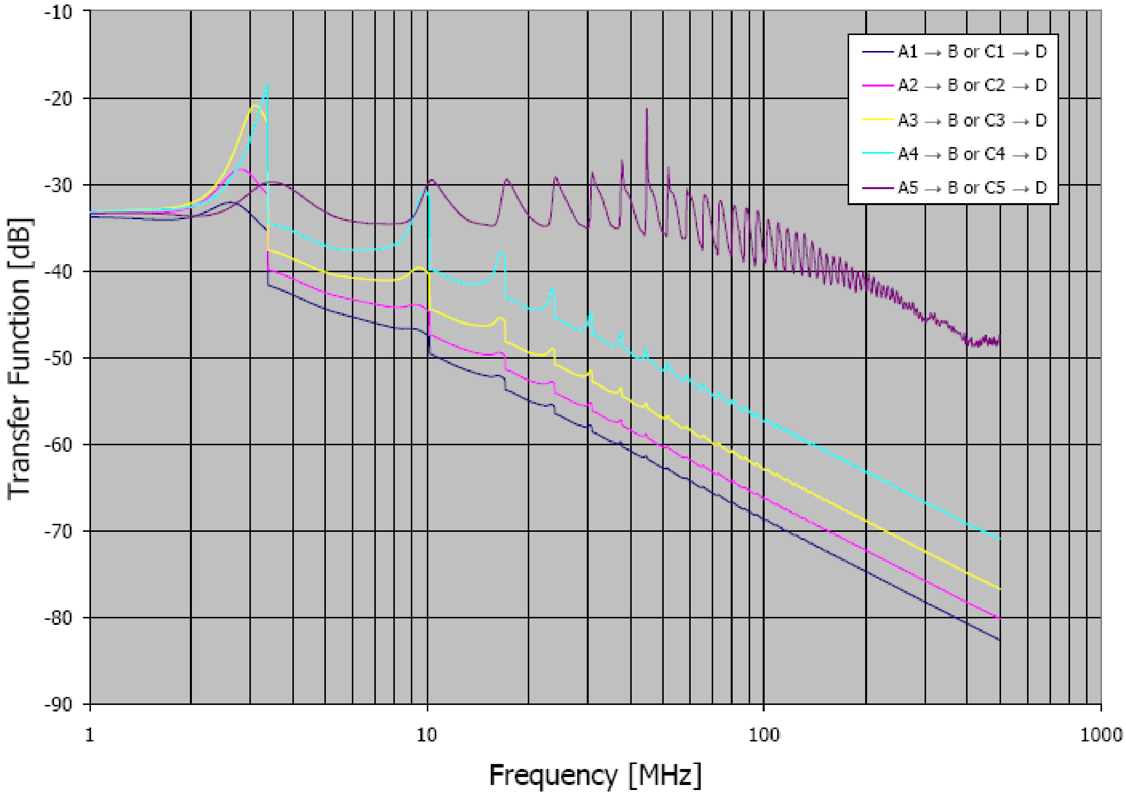


Figure 4.16: Calculated TFs from both terminations

Measuring Cable

The transfer characteristics of the RG-213 measuring cables used is shown in figure 4.17. It shows measured and calculated values for 10m, 15m and 45m long measuring cables. From the graph it is evident that the cable attenuation increases with increasing frequency. As a result, the sensitivity of the measuring system naturally decreases with increasing frequency. This follows that longer measuring cables exhibit higher attenuation.

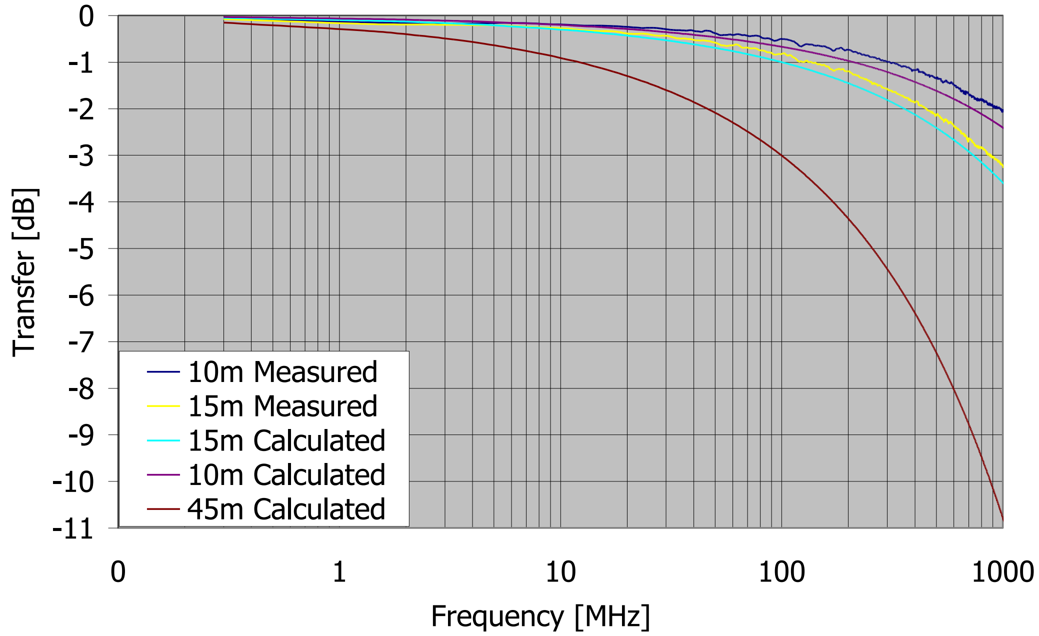


Figure 4.17: Calculated and measured transfer function of different lengths of measuring cables.

PD sensor

As discussed before, internal or external sensors can be applied in power cables. In practice, mainly external high-frequency current (HFCT) probes are used. The sensitivity of a sensor can be expressed as its input impedance as function of frequency. Taking 50 Ohm as a reference, this can be transferred into dBOhm by applying the formula 20*log(Re(Zin)/50[Ohm]). The input impedance can be measured using a network analyze, see figure 4.18. For all three sensors this unpredictable behavior is due to the fact that the sensor is operated outside its operational bandwidth: the HFCT sensors are designed to measure signals up to 5 MHz. Nevertheless, the response of the HFCT sensors at higher frequencies is high enough to measure PD signals with good sensitivity higher than 0 dB.

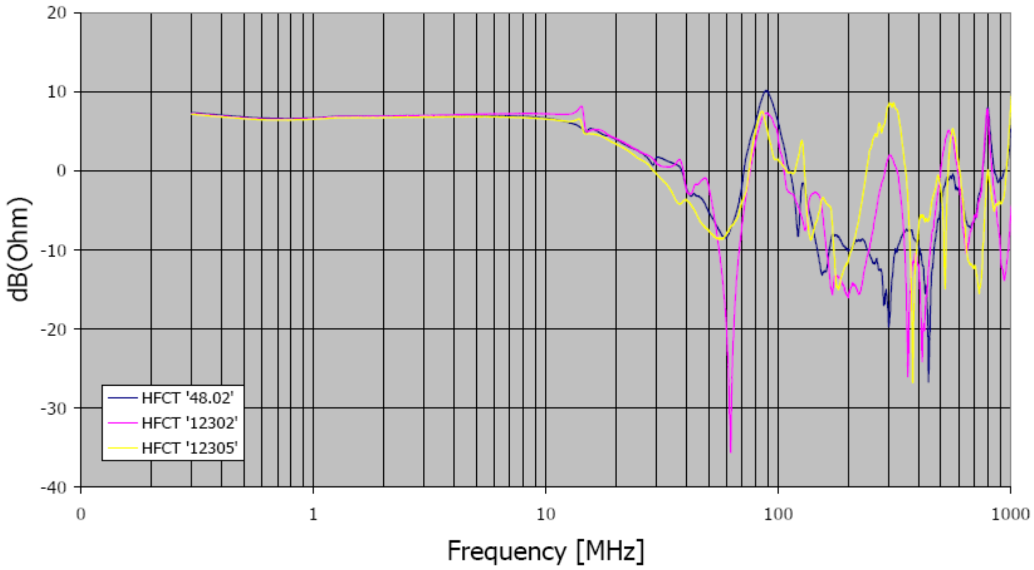


Figure 4.18 Frequency responses of three different HFCT sensors

Some power cable terminations are equipped with internal PD sensors, which are installed during the assembly of the termination. We assume that the defect inside the cable accessory is located at point A, because we determine the TF from A to B. The results of the measurements are shown in figure 4.19. As we can see, the internal PD sensors have a much higher TF than the externally current probes, and thus can provide higher sensitivity.

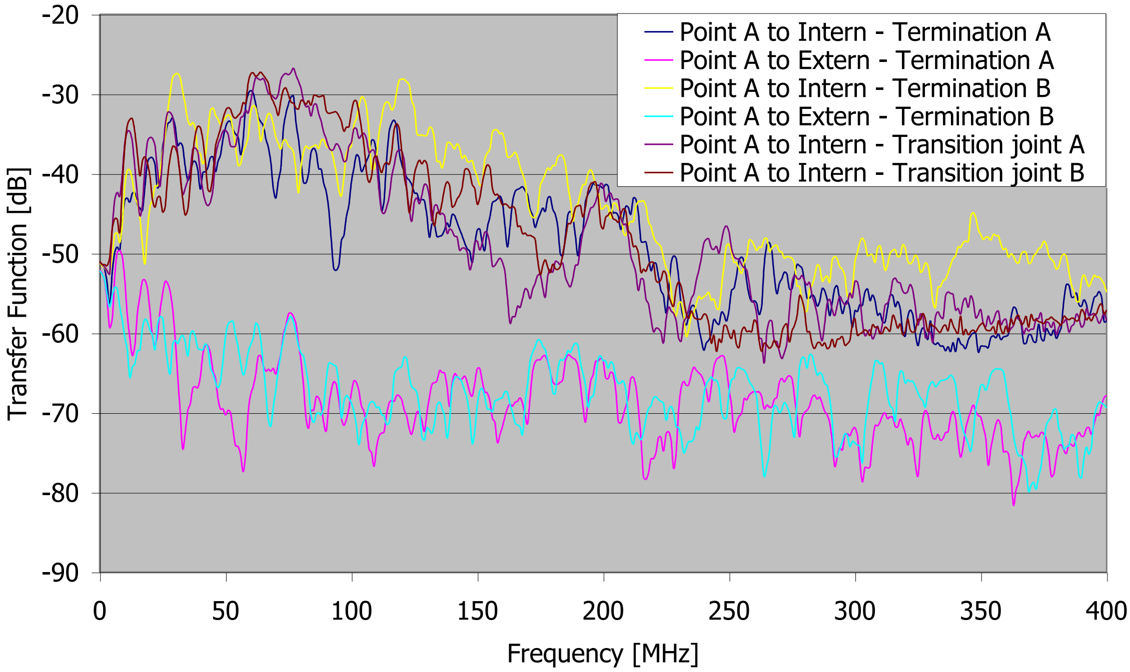


Figure 4.19 Transfer function plots to compare internal PD sensors (yellow, blue, purple and brown lines) with external PD sensors (blue and pink lines).

4.3 CONCLUSIONS

In this section the sensitivity of the RF technique was studied in the case of power cables. Generally the factors that affect the sensitivity of the system can be summarized in the table 4.1 below.

Table 4.1 How different factors affect the sensitivity of the RF technique in cables.

Factors affecting sensitivity	
Sensor	Depending on the transfer function of the sensor: the higher and the flatter the response the better.
PD location in termination	Very small differences might occur in the TF, but since the signal is mostly attenuated from the top, the sensitivity should be higher for lower locations
Power cable under test	Depending on the cable type the attenuation of the RF waves is different. In general attenuation of the RF waves is high and large terminations might be affected at higher frequencies.

4.4 REFERENCES

[1] S. M. Markalous, S. Tenbohlen, K. Feser: Improvement of acoustic detection and localization accuracy by sensitive electromagnetic PD measurements under oil in the UHF range, 14th International Symposium on High Voltage Engineering, Beijing, China, 2005

[2] L. Lundgaard et.al (Task Force 15.01.04): "Partial Discharges in Transformer Insulation", CIGRE Paris, august 2000. Paper 15-302

Part V
Performance checks: System sensitivity, set-up on-site including test object

5.1 INTRODUCTION

In addition to the conventional method according to IEC 60270, both UHF and acoustic techniques are used for measurements in GIS. Several parameters influence the sensitivity of these techniques. As stated before, the primary quantity of interest (the PD magnitude) cannot be evaluated from the signals measured at the terminals of a coupler: calibration using the IEC 60270 method is not possible. However, as described by joint TF 15/33.03.05, a verification of the detection sensitivity can be performed and has proven to be useful in practice for gas-insulated systems [5.1]. In this section, a summary of the described method for GIS is given and a similar procedure is proposed for other high-voltage assets such as power transformers and transmission cables. Although the examples presented are obtained using the VHF/UHF technique, a similar procedure can be followed for other non-conventional techniques such as the acoustic detection technique.

5.2 SENSITIVITY CHECK FOR GAS-INSULATED SYSTEMS

In general, the following steps have to be performed to obtain and check the detection sensitivity of the UHF detection technique for GIS. This procedure is described in more detail by Cigre TF 15/33.03.05 in Electra [5.1].

Step 1 (laboratory test)
First, an artificial electrical pulse is created which emits a signal similar to that from a real defect that causes a defined level of apparent charge (e.g. 5 pC in case of GIS).

Step 2 (field test)
Secondly, this artificial electrical pulse is injected into the GIS on-site in order to check the ability to detect this pulse on sensors being evaluated using the appropriate measuring equipment.

5.2.1 Step 1: laboratory test

A laboratory test has to be performed to determine the amplitude and pulse-shape of the artificial pulse representing a real discharging defect. For that purpose, a defect (e.g. a mobile particle) is located near sensor S1, see Fig. 5.1. Voltage is applied to initiate partial discharges and the PD magnitude is measured using a detection circuit according to the IEC 60270 recommendations.

Simultaneously, the frequency spectrum or UHF pulse that is detected is measured at sensor S2, see figure 5.1. This gives the relation between PD magnitude and UHF signals detected with this specific measuring setup. It should be noted that this result is only valid for this specific type of sensor and measuring equipment used.
The next step in the laboratory test is to inject artificial pulses into the sensor S1. The pulse shape and/or magnitude is adjusted until a comparable measurement is obtained from sensor S2, see Fig. 5.2. In the example for a mobile particle giving 5 pC as illustrated here, an artificial pulse of 10 V gave similar results.

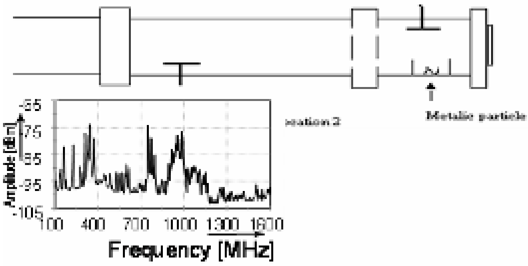


Fig. 5.1: Step 1 of laboratory test: discharging defect at location S1 giving a certain PD magnitude (mobile particle giving 5 pC discharge level).

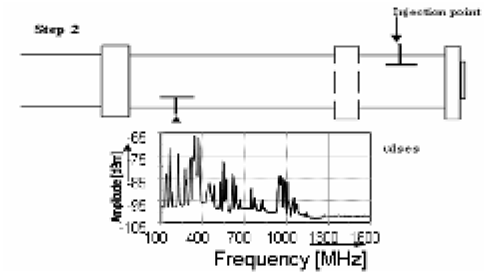


Fig. 5.2: Step 2 of laboratory test: injecting artificial pulses to excite a similar frequency spectrum as the discharging defect giving a certain PD magnitude (mobile particle giving 5 pC discharge level).

5.2.2 Step 2: on-site test

The on-site test can be carried out under operation. To test the sensitivity of the sensor-measuring equipment arrangement in the field, the artificial pulses as found in the laboratory test are injected in one of the sensors and the response on the adjacent sensor is measured. If the artificial pulses can be detected, the check is successful and it is shown that for this type of GIS equipment, this type of sensor and this type of measuring equipment, a sensitivity of at least 5 pC for mobile particles can be reached, see figure 5.3.

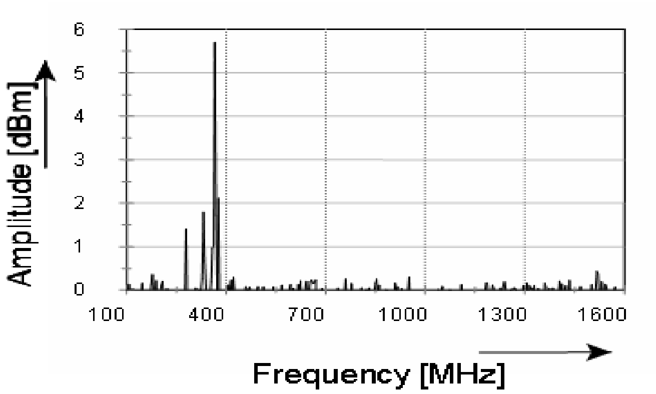


Fig. 5.3: Successful on-site test: the injected artificial pulse of 10 V on one sensor simulating a 5 pC mobile particle was detected.

This on-site test has to be repeated for all couplers present in the substation.

5.3 PERFORMANCE CHECK FOR POWER TRANSFORMERS

For detection of PD in power transformers, UHF probes as in Fig. 3.3 can be installed during operation and will give the ability to measure UHF signals from inside the transformer tank. Up to now it has been difficult to check the technical performance values of the mounted and inserted UHF probes. As a result of this problem, two different methods of a so-called Performance Check were investigated. During the Performance Check the verification of the whole signal path including the UHF probe, the measuring lines and the PD acquisition unit is essential.

In a single port Performance Check, artificial UHF impulses are injected insulated from the receiving path while the injected impulses are detected with the receiving path of one and the same probe. A dual port Performance Check uses a second UHF probe to inject the artificial UHF impulses to demonstrate the functionality of the first UHF probe. Therefore a second port, e.g. a second oil valve is needed. The main difference between the two methods is the fact that in the case of the dual port Performance Check, electromagnetic waves have to be transmitted through the transformer tank. It is sufficient for the single port Performance Check to use a capacitive coupling of high frequency signals, realized by the UHF PD probe mentioned in chapter 2. To achieve the same signal to noise ratio, the dual port Performance Check needs a signal generator with higher output power. This is because of the necessity to increase the wave emission. The check may be expanded to a Sensitivity Check as will be discussed in chapter 5.3.2.

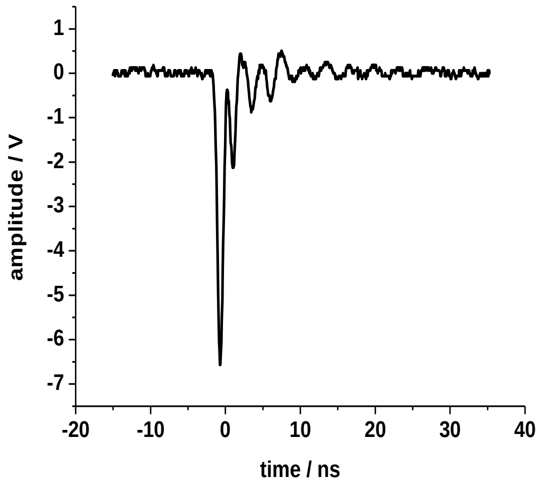


Fig 5.4: Time signal of a UHF signal generator

For the following investigation of the Performance Check the artificial PD signal is injected from an impulse generator, see Fig. 5.4. The related frequency spectrum is comparable to a PD source. For example, the signal generator may feature signal rise times shorter than 300 ps with a pulse width of less than 450 ps into a 50-Ohm impedance. The corresponding frequency spectrum includes components up to 1.25 GHz.

5.3.1 Single Port Performance Check

In this example of a single port performance check an insulated monopole was integrated inside the UHF-probe, see figure 5.5a. The injection of the presented UHF-impulse caused a coupling of the UHF signal to the probe head and allowed the following Performance Check. Therefore two parallel lines inside the probe frame for transmitting and receiving are necessary. A precondition of a correct Performance Check is the prevention of direct cross coupling of signals from the transmitting to the receiving line. The line lengths are used for an approximation of the signal propagation time of 6 ns in case of solely coupling from the integrated monopole to the probe head. The theoretically estimated propagation time was demonstrated in a separate laboratory test, e.g. there is no direct cross coupling of signals.

Another precondition for a successful Performance Check is the recognition of an inaccurate probe installation. One fault might be the galvanic contact of the probe head within the oil valve or the transformer tank due to incorrect mounting and the resulting grounding. In that case, no high frequency signals may be detectable. During a reference measurement check the completely installed UHF probe with integrated monopole lying on a wooden table is physically grounded. The resulting detectable signal has a frequency spectrum without significant high frequency components (see Fig. 5.5b, grounded probe).

The method of the Performance Check is investigated finally on a test transformer tank inside the laboratory. The described signal generator is used and a transient recorder with the analogue bandwidth of 2 GHz. After injecting the artificial UHF-impulse the signal with the corresponding frequency spectrum (see Fig. 5.5, thin red line) was detectable. High frequency components up to 1.25 GHz are clearly recognizable. Hence it could be demonstrated that the complete receiving path from the UHF probe to the PD acquisition unit is correctly installed.

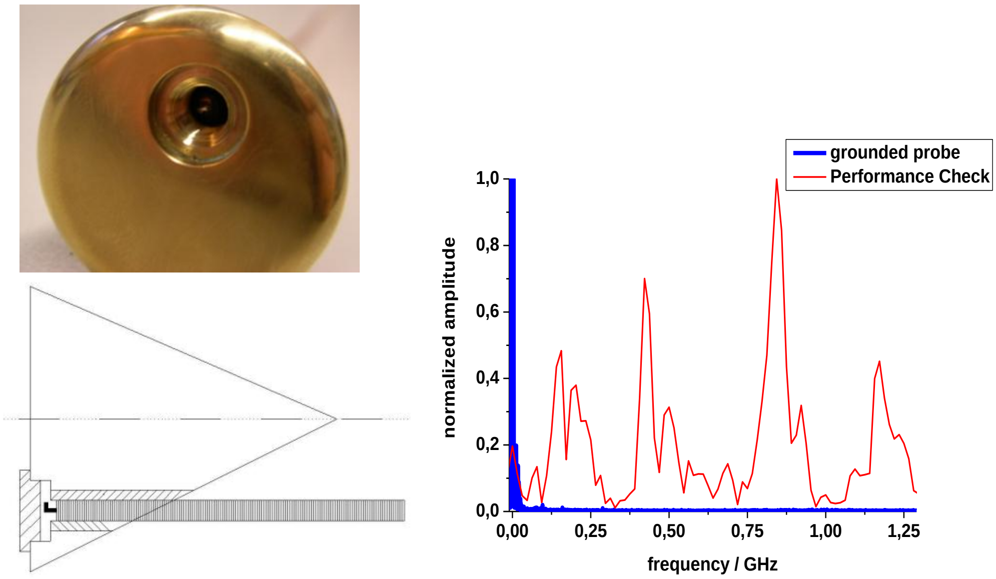


Fig 5.5: UHF sensor with integrated monopole (left) and Spectrum of the grounded probe (thick blue line) in the comparison to the error free probe in the transformer tank (thin red line) using same injected signal (right)

The Performance Check fulfils its task to check whether the UHF-probe and the UHF measuring system are correctly installed.

5.3.2 Dual Port Performance Check

With an existing second oil valve a dual port Performance Check is possible. In an example laboratory test a monopole oil valve probe was installed into a second oil valve of the test tank. The UHF signal from the previously described UHF signal generator could be received with the UHF probe. The corresponding spectrum can be seen in Fig. 5.6.

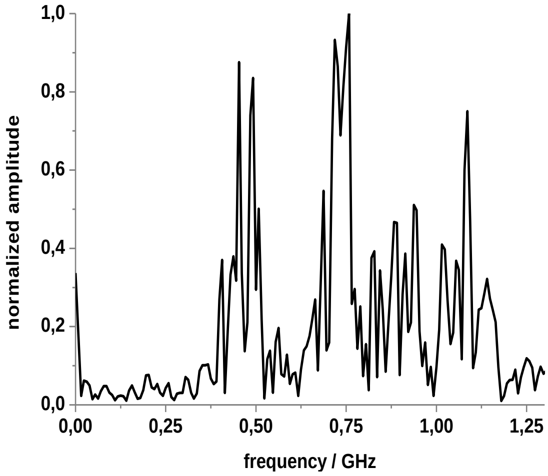


Fig 5.6: Spectrum of the dual port Performance Check

The coupling of electromagnetic signals via electromagnetic wave transmitting through the transformer seems to work well like the capacitive coupling inside the UHF PD Probe.

The dual port Performance Check fulfils the same task as the single port solution but is not applicable where no second oil valve or other type of UHF sensor mounting position is available.

5.4 SENSITIVTY CHECK FOR POWER TRANSFORMERS

To evaluate the detection sensitivity of the UHF method compared to a detection circuit according to the IEC 60270, a similar procedure as is being applied to GIS (section 5.2) can be defined. It consists of the following steps:

1) In a laboratory setup use a PD-source with known partial discharge magnitude (in pC) is located close to sensor 1. Measure the output signal or frequency spectrum of the coupled signal to sensor 2.
2) Use a pulse generator to inject artificial PD pulses at sensor 1 and change the amplitude until is the signal detected at sensor 2 is comparable with that detected at sensor 2 originating from the PD source in step 1.

Fig. 5.7: Examples of artificial PD sources in a power transformer during the laboratory test of the sensitivity check: a) using a spark plug and b) using an artificial source in a coupler pocket.

From this test, the relation between calibrated PD magnitude and artificial pulse is known for a certain propagation path. This can be used on a power transformer to test the sensitivity of the UHF coupler arrangement by the step:

3) Sensitivity check of the UHF coupler arrangement on the power transformer by injecting the pulse shape found at step 2 on each of the placed couplers and detect at the other couplers. If the injected signal is detected, this means that between the UHF-sensors the sensitivity is high enough to detect partial discharge activity with a certain magnitude in pC as defined at step 1.

Compared to GIS, for the case of power transformers the following differences are encountered:

1. More complex internal structure which results in different responses even between similar designs;
2. Less standardized designs;
3. How to make laboratory setup, specifically, for relevant defects to determine the relation pC-UHF;
4. Influence of propagation effects between defect and sensor(s);
5. How to test on-site with only few sensors installed.

In the following sections, examples are presented.

5.4.1 Laboratory test

As described before, the first step in the laboratory test is measuring the emitted signals from an artificial PD source using both UHF and IEC 60270 detection circuits. In literature, many investigations have been published and will be presented as examples below.

5.4.1.1 How to make artificial PD sources in a power transformer

Figure 5.7 shows two examples of making artificial defects that are inside or virtually inside the power transformer. Figure 5.7a shows the application of a

spark plug, mounted on the top cover of the transformer tank. Using an external voltage source, the spark plug can be energized and will produce sparks inside the power transformer, simulating a real discharging source.
Figure 5.7b shows an artificial PD source (rolling ball in oil) inside a dielectric coupler pocket. Due to the fact that it is located inside a pocket, it is virtually inside the power transformer. This artificial source is energized externally and the signals will propagate into the power transformer.
If it is possible to open a hatch cover on the top of the transformer, an artificial source, connected to a stick or rope can be lowered in the transformer to a certain position. Again, an external source is used to energize the source and PD pulses propagate through the transformer.

5.4.1.2 Comparing results from UHF and IEC60270 detection circuits

Figure 5.8a shows the pattern as obtained from the spark plug as was shown in figure 5.7a. Moreover, it shows the reading from the IEC 60270 detection circuit, giving about 15 pC.

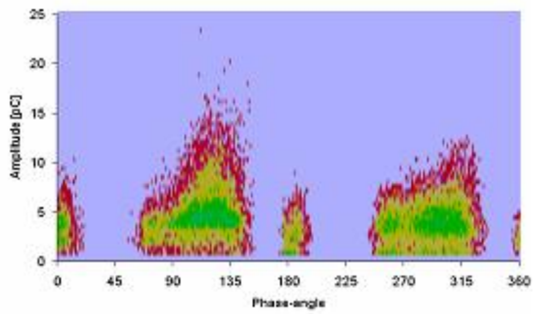


Fig. 5.8: Measuring results obtained using a detection circuit according to the IEC 60270 recommendations, coming from a spark plug giving 15 pC.

The PD level of the rolling ball test cell, inserted in the coupler pocket was calibrated in a separate test setup, giving 50 pC of PD magnitude.

The detected signals using a UHF detection circuit are shown in figure 5.9. Although in the sensitivity check procedure for GIS as described in [5.2] the results are measured in frequency domain, the results measured as phase-resolved PD patterns are more often used. This mainly depends on the type of detection circuit (narrow or wide band). In case of the spark plug, the frequency spectrum was detected at a UHF-sensor (sensor 2), which is positioned at a distance of 2 meters from the spark plug, see figure 5.9a.
In case of the artificial defect inside the coupler pocket, the response was measured in the phase-resolved domain, see figure 5.9b. This pattern was recorded using a wide band UHF detection system at a UHF sensor (sensor 2), which was located 6 meters away from the defect.

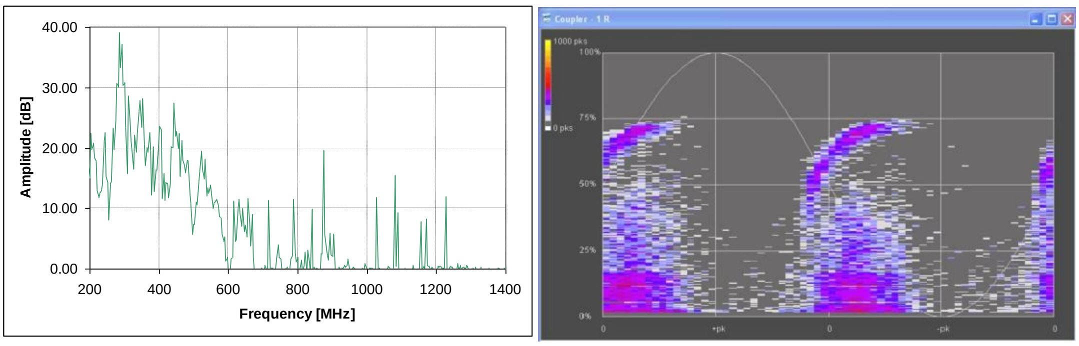


Fig. 5.9: Measuring results obtained using a narrow band detection system coming from a spark plug (signal-to-noise ratio spectrum) (left) and a wide band detection system coming from an artificial defect located in a coupler pocket (right).

5.4.1.3 Artificial pulses to simulate a discharging defect

Fig. 5.10: Location of a) the sparkplug, coupler #1 which is used to inject artificial pulses and coupler #2 which is used to receive the signals and b) the artificial defect replace by a UHF sensor in the coupler pocket.

The final step in the laboratory test is to simulate the obtained UHF response shown in figure 5.9 by injecting artificial pulses on a sensor (sensor #1) located at the same location or close to the location of the artificial defect, see figure 5.10.

These couplers (sensor #1) are being used to inject artificial pulses. In case of the spark plug, the voltage level of the artificial pulse generator or calibrator had to be adjusted to 14.2 V to give a comparable frequency spectrum in the frequency range between 200 MHz up to 700 MHz, see figure 5.11a. This result gives us the relation of 1.5 V/pC which can be used in further experiments to check the sensitivity of the UHF-sensor #2 regarding a PD-source close to UHF-sensor #1. If more than two sensors are present, this procedure is repeated for all sensors.
In case of the artificial defect in the coupler pocket, artificial pulses of 10V had to be injected to represent the signals in a wide frequency band, see figure 5.11b. This gives the relation of only 0.2 V/pC.
While the discrepancy may seem large there are a number of factors that affect the calibration of such a test. The V/pC levels determined will depend on

1) the sensitivity of the UHF coupler;
2) the position of the UHF couplers, e.g. direct line of sight;
3) type of PD source used as a reference;
4) configuration of the circuit used to apply the IEC60270 calibration to the reference PD source;
5) size of the tank in which the UHF calibration measurement is made, and
6) most importantly, on the rise time and shape of the injected pulse.

With regard to the above mentioned example, bearing in mind all of these factors and the likelihood that detection levels of interest for in-service power transformers will probably exceed PD levels of hundreds of [pC], it seems clear that a pulse injection of some 10s of volts would be a fair basis for a sensitivity

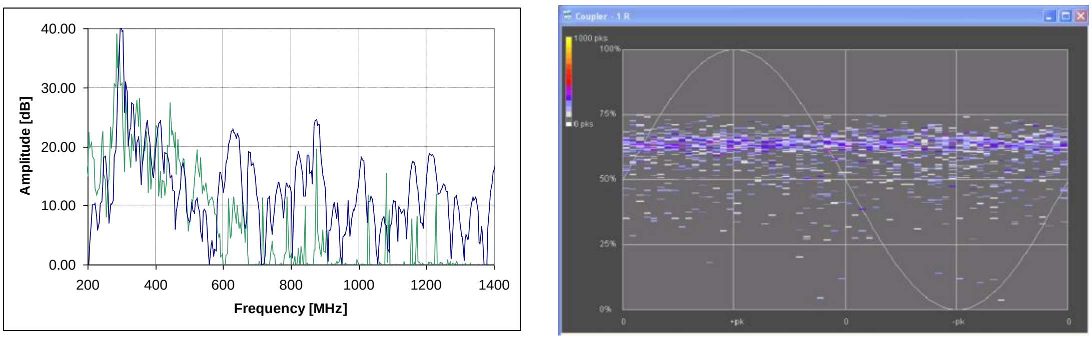


Fig. 5.11: Measuring results obtained using a) a narrow band detection system coming from 14.2V artificial pulses (signal-to-noise ratio spectrum) and b) a wide band detection system coming from 10V artificial pulses.

test provided the pulse shape satisfies certain criteria.
In general it is not possible to perform a laboratory test for each type and design of power transformer. Therefore, more research is required to investigate the possibility to generalize the laboratory test to define the relationship between pC-UHF and injected volts [5.10].

5.4.2 On-site test

As mentioned above, it is rarely possible to perform a laboratory test on a similar type and design as is present on-site. So although the results of the sensitivity check previously described have been obtained on a 14 MVA transformer in the laboratory, the effect of the oil alone on the propagation of high-frequency signals is approximately similar for all types of transformer oil. However, the influence of the interior construction and size of the transformer has the biggest influence but again, it is impossible to perform the first two steps of the sensitivity check for each transformer separately.

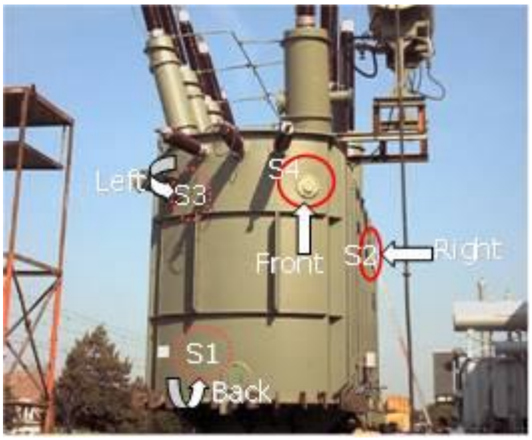


Fig. 5.12: Example of on-site sensitivity check on a 500 MVA power transformer. In dielectric windows W1...W4 the sensors S1…S4 are installed.

5.4.2.1 On-site test on transformer with dielectric windows

As stated in the introduction, in this example the sensitivity is tested by injecting the 45V pulses (which represents about 30 pC in the 14 MVA transformer) in external UHF-sensors mounted against dielectric windows and distributed on the tank of a 500 MVA transformer, see figure 5.12.

Figure 5.13 shows the detected frequency spectra at the three UHF-sensors W1, W2 and W3 (blue graphs), when 45V pulses are injected into UHF sensor W4. The background noise at each UHF-sensor is also displayed for comparison reasons (purple graphs). From the figures the following observations can be made:

1) the injected pulses can be detected at all three UHF-sensors located;
2) the amplitude of the spectrum is highest at UHF-sensor W2. This can be

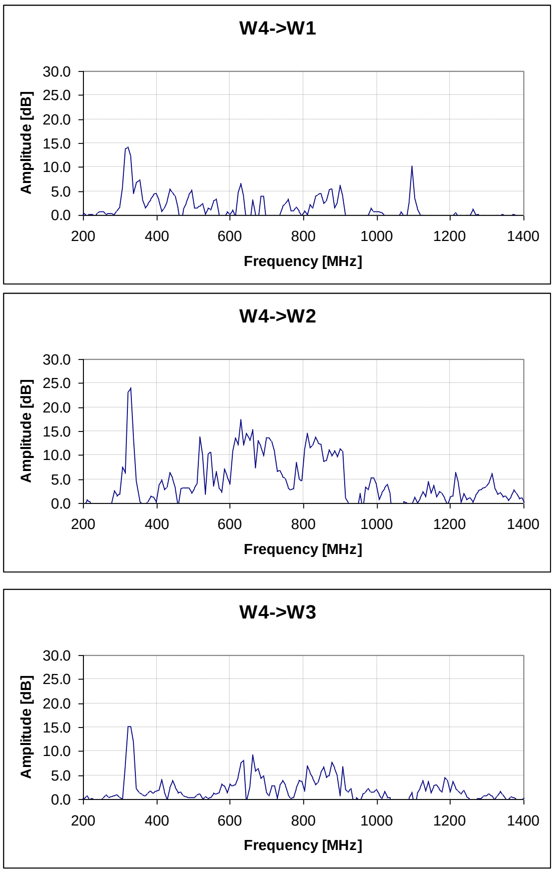


Fig. 5.13: Examples of signal-to-noise ratio frequency spectra from injected pulses in UHF sensor W4 detected at W1, W2 and W3.

Fig. 5.14: Laboratory setup (left picture) used to simulate the on-site step of the sensitivity check using an internal sensor through the oil valve (middle picture) and injection using a sensor through an opening in the top cover of the transformer (right picture).

explained by the fact that couplers W2 and W4 are in a direct line of sight and a direct coupling path is present;

3) The frequency range with good signal-to-noise ratio is from 600 up to 900 MHz.

5.4.2.2 On-site test on transformer with internal sensors

As a second example, artificial pulses were injected in a laboratory environment to test the sensitivity of an internal UHF sensor inserted via the oil-drain valve, see figure 5.14.

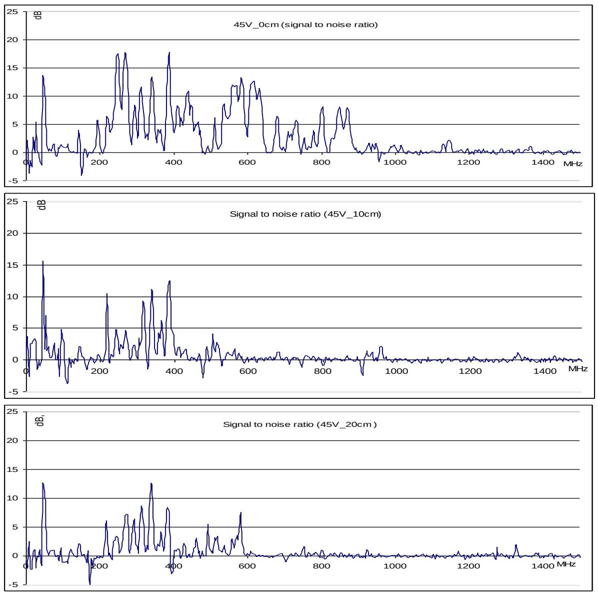


Fig. 5.15: Signal-to-noise ratio spectra obtained at three different depths for the internal sensor, from top to bottom: fully inside, just outside and fully outside.

A 50 mm (2”) diameter oil valve sensor has been inserted into the transformer and was put to different depths inside transformer tank. Artificial pulses of 45V were injected through an opening in the top cover of the transformer, see figure 5.14. The frequency spectra obtained at different depths were measured. The length of the sensor is 10 cm. At first, the sensor part is completely inside the transformer. Then it is pulled back in several steps: first only 4 cm left inside, then 0 cm inside, then 5 cm, then 10 cm inside the valve. The frequency spectra (signal-to-noise ratio) with the sensor fully inside the transformer, just outside (0 cm) and fully outside are shown in figure 5.15.

Considering all five positions of oil valve sensor and obtained frequency spectra it is evident that as long as some part of the sensor is inside the transformer, the spectra shows higher spectral behavior. As soon as the sensor is outside the transformer and inside the oil valve itself, it is shielded for the signals inside the transformer. For easy comparison, the indicator *measured power*, which is proportional to the energy in the frequency spectrum, is calculated and plotted for the different distances, see figure 5.16. As it could be seen from the spectra, the measured energy decreases dramatically as soon as the sensor is outside the transformer.

A newly developed UHF signal generator offers the possibility to inject a voltage step with variable amplitude between 0 V and 60 V. Its signal rise time is shorter

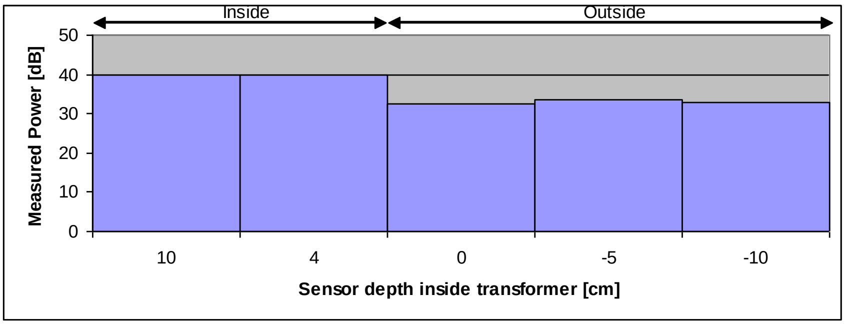


Fig. 5.16: Energy-indicator measured power for different penetrating depths of the sensor into the transformer.

than 100 ps, which results in a corresponding frequency spectrum up to 2.5 GHz. The optional synchronization to the applied voltage via a photodiode can be seen in the phase resolved Partial Discharge pattern (PRPD), see Fig. 5.17.

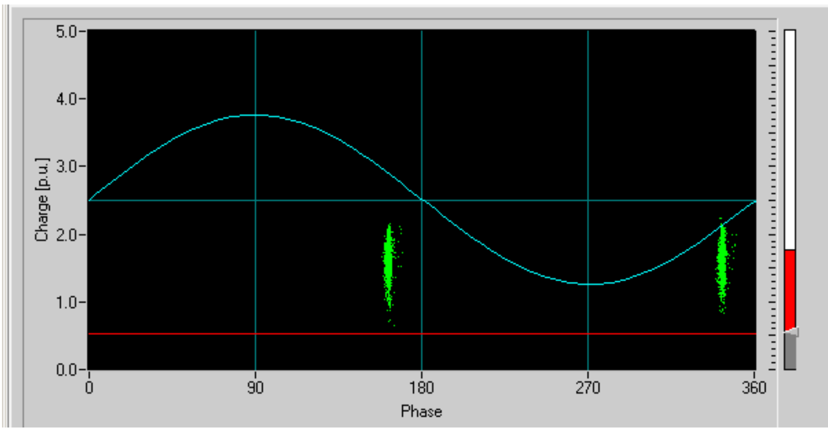


Fig. 5.17: Phase Resolved Partial Discharge pattern (PRPD) of the new UHF signal generator

For signal propagation times of UHF PD signals in the range of nanoseconds compared to the cycle duration of 20 milliseconds, e.g. for 50 Hz, the measurement of Phase Resolved Partial Discharge (PRPD) patterns is useful since UHF PD patterns will remain essentially unchanged as related to electrically recorded PD patterns. Fig. 5.18 shows the test tank in the laboratory with two attached UHF probes. However in [5.10] has been shown that the pattern for one simple source with a tip curvature and given voltage may also be depend on setting of the measuring system.
The test tank is filled with oil and is completely closed. The two oil valves are installed approximately two meters away from each other.

An electromagnetic coupling between the two probes has to be a wave based coupling because of wavelengths smaller than 0.75 m for frequencies higher than 300 MHz. For the investigation of the sensitivity verification the new UHF signal generator feds one probe with variable output voltage. The quantitative Fast Fourier Transform (FFT) of the measured signals from the receiving probe is shown in Fig. 5.19. It follows that considering given pulse injected with a given propagation path to the source linearity has been observed. It would be misleading to claim the same for a PD source in general with an unknown position inside the test object. It follows that considering given pulse injected with a given propagation path to the source linearity has been observed. It would be misleading to claim the same for a PD source in general with an unknown position inside the test object.

Fig. 5.18: Test tank with two oil valves and two flange-mounted UHF probes

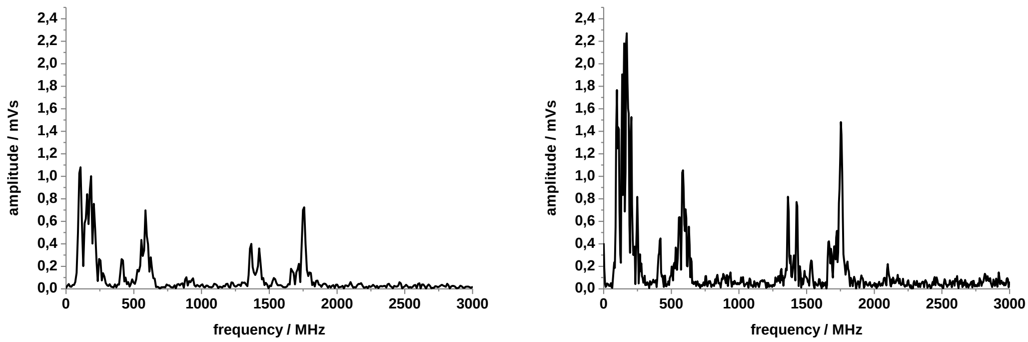


Fig. 5.19: Sensitivity verification with variable output voltage: Linear ratio

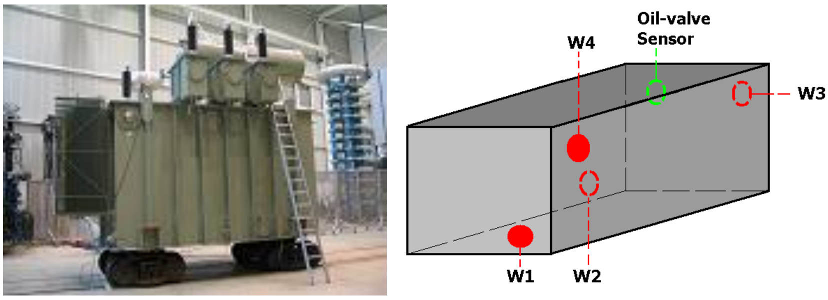


Fig. 5.20: Reactor and schematic diagram of the positions of the 4 external UHF sensors and one internal sensor inserted through the oil-valve of the tank.

between voltage of excitation signal and frequency components

The results show a nearly linear ratio between the magnitude of the excitation signal and the frequency components of the received signal. The linear relation seems to be valid over the whole frequency range up to 2 GHz. E.g. the frequency fraction around 1.75 GHz rises from 0.7 mVs up to 1.4 mVs if the feeding signal rises from 30 V to 60 V. Existing UHF PD acquisition units offer the

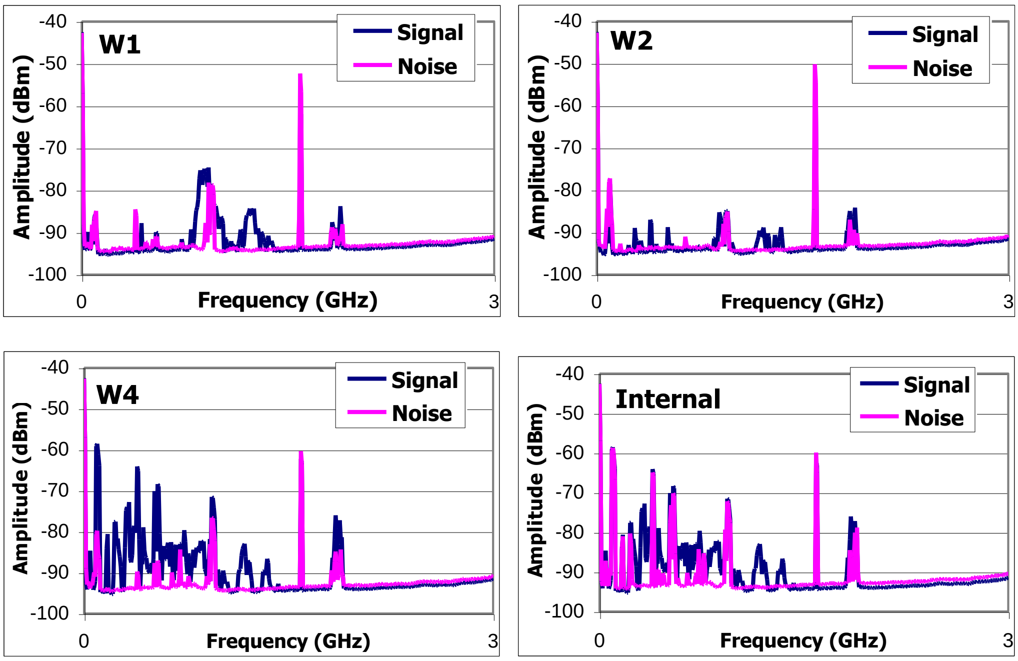


Fig. 5.21: Recorded spectra at sensors when injecting at sensor W3.

possibility to measure signals within a small bandwidth (narrow-band equipment). Further investigations will show whether the reading quantity in mV over a defined frequency range is useful for a sensitivity verification or check as mentioned above. Other reading quantities or post processed quantities as e.g. the signal power or energy may also be useful and should be focused in future.

5.4.2.3 On-site test on transformer with external and internal sensors

A third example shows a combination of four external sensors and one internal sensor through the oil-valve, fitted on a reactor, see figure 5.20.

The sensitivity check was performed by injecting 45V pulses in all sensors. Examples of spectra measured at the three external sensors and the internal sensor when injecting in external sensor W3 are shown in figure 5.21. It is clear that only few signals are picked up on sensor W1 and W2, the best response is on W4 and the internal sensor. The fact that W2 is picking up only few signals is surprising as it is rather close to W3.

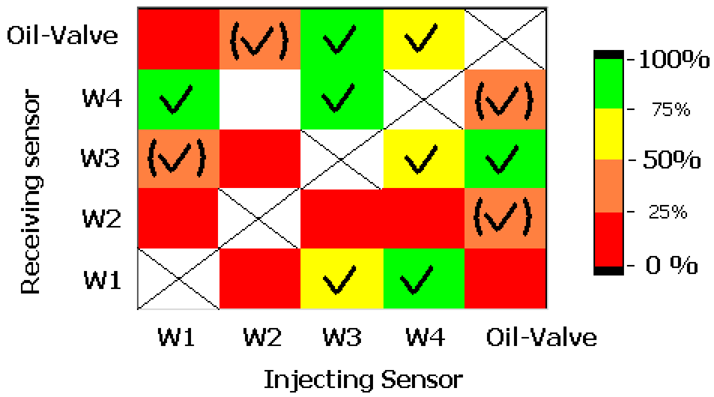


Fig. 5.22: Sensitivity matrix obtained from injecting a 45V pulse in one sensor and measuring at the others. A "✓" indicates that the signal is strong and easy to be detected; a "(✓)" indicates a weaker signal but strong enough to be detected.

A summary of all injection measurements is shown in figure 5.22.
From figure 5.22 can be concluded that sensor W2 is not able to detect any of the signals injected on the other sensors. The signals are somehow blocked. However, looking

for example at all sensor pairs involving W4, the sensitivity between these sensor-pairs is proven.

5.4.3 Concluding remarks

Based on the results described in this paper the following can be concluded:

1. Examples have been given about what is the required sensitivity and how to model this in laboratory.
2. There is a significant difference in the response of sensors located inside or outside the transformer vessel.
3. The best way to perform the laboratory test, specifically the installation of an artificial defect inside a similar transformer as on-site, needs further investigations;

Further agreement has to be reached on the following items:

a. the sensitivity of the UHF coupler and how to define it;
b. the position of the UHF couplers, e.g. direct line of sight;
c. the type of UHF coupler, e.g. internal and external;
d. the number of UHF couplers needed to give sufficient coverage of the equipment
e. suitable materials for dielectric windows for reliable, long-term operation.
f. the type and design of dielectric windows to be applied for external sensors;
g. type of PD source used as a reference (in collaboration with experts on transformer insulation);
h. configuration of the circuit used to apply the IEC60270 calibration to the reference PD source, e.g. to full set-up or only artificial defect;
i. size of the tank in which the UHF calibration measurement is made,
j. most importantly, on the rise-time and shape of the injected pulse.

5.5 SENSITIVTY CHEK FOR TRANSMISSION POWER CABLES

In the recent years for after-laying tests of new installed accessories of HV power cable unconventional PD detection is becoming slowly a common practice of on-site testing (after-laying) [5.7, 5.8]. With regard to this application the following can be considered:

a) Non-conventional PD detection circuits are based on high frequency electromagnetic signals Radio Frequencies (RF) up to 500MHz;
b) The measuring circuit can not be calibrated according to IEC 60270 -> no [pC] reading;
c) The reading depends on the high-frequency response of HV components, PD sensor type and PD detection circuit [5.9];
d) Each particular configuration needs specific reading adjustment of the complete detection circuit before it can be used for on-site testing. This is due to diversity of RF sensor types available (e.g. internal, external, inductive, capacitive), different construction types of accessories as well as different possibilities for signal amplification and processing (e.g. narrow band, wide band, spectral analysis, wideband integration), see Fig 5.23;
e) Sensitivity in [pC] of the circuit consisting of particular type of the cable accessory, RF coupling unit (PD sensor) as well as the RF PD detector can be determined by means of a sensitivity check.

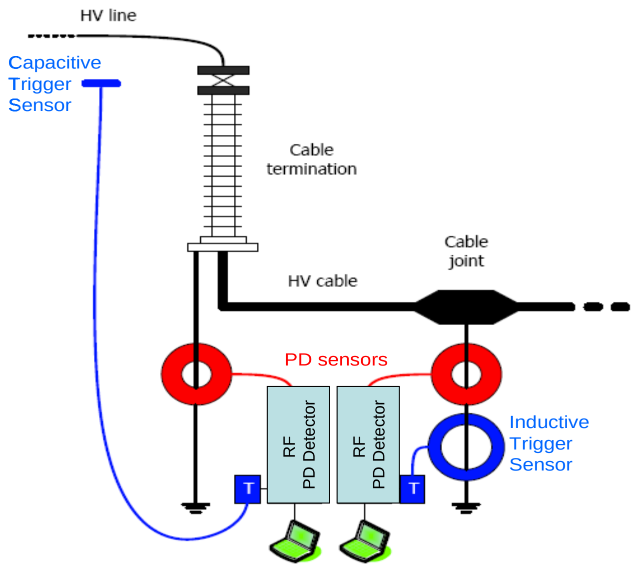


Fig. 5.23: Schematic example of unconventional PD detection circuit as used for HV power cables.

Compared to GIS and power transformers, for the case of transmission cables, the following differences are encountered [5.3, 5.4]:

1. Similar construction to GIS, however no possibility to insert artificial internal defect without disturbing the uniform geometry or integrity the cable;
2. Few locations are available for the installation of sensors: near termination or inside the termination; inside the joints or near the joint if a grounding cable is present;
3. How to make laboratory test, specifically, how to introduce a critical defect to determine the relation pC-mV;
4. How to perform the test on-site with only few sensors installed, especially at joints.

Based on the experiences obtained for GIS, also for power cables sensitivity-check procedures have been proposed and used in the field [5.4]. In particular, to determine the meaning of these amplitudes and to estimate the sensitivity level of RF devices, laboratory and on-site procedures have been introduced. To perform the laboratory test in case of cable systems, a laboratory setup as shown in figure 5.24 can be used.

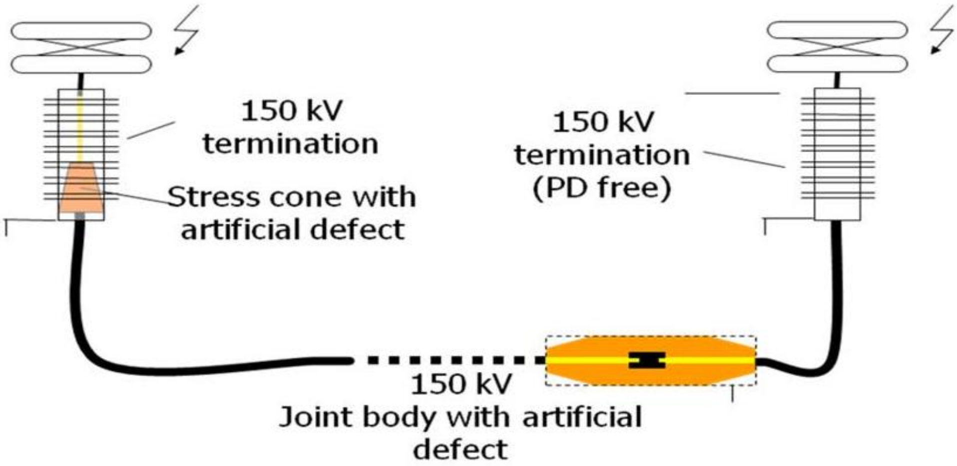


Fig. 5.24: Example of a suggested laboratory setup for the first step in the sensitivity check for cable systems.

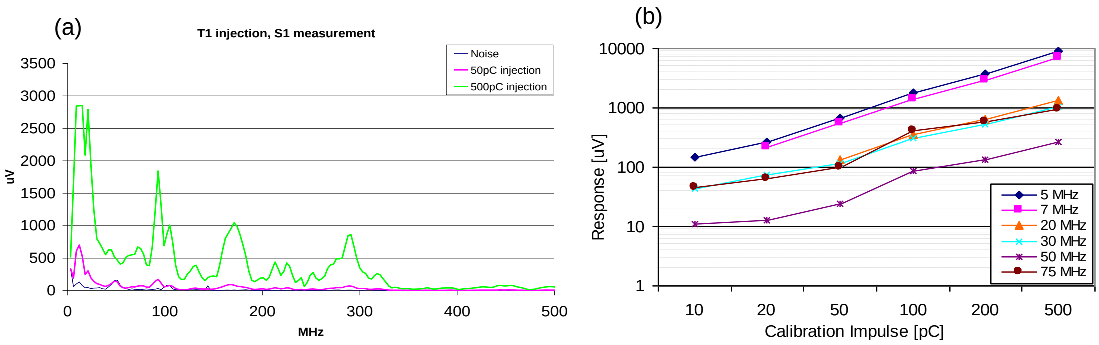


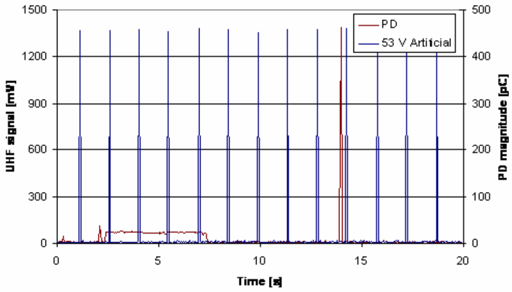
Fig. 5.25: Examples

a) RF spectrum of PD pulses 50pC and 500pC as injected on the cable termination T1 and measured using internal sensor S1 at the same termination;

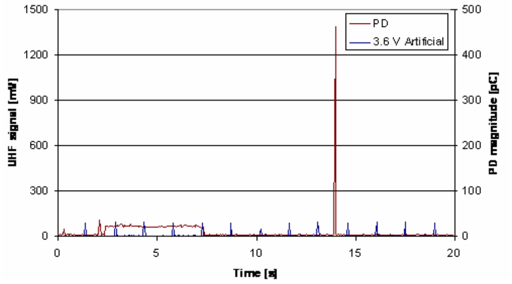
b) Response of the RF PD detection system to calibration impulses at different measuring frequencies. For a particular combination of test object/ PD sensor type the [pC] / uV ratio depends on the selected VHF/UHF frequency band

<u>Laboratory procedure</u>

1. Installation of an artificial PD defect (e.g. PD level below 100pC) on a full size cable system, see figure 5.24
2. Installation of given type of HF/VHF sensors including RF PD detection system on the cable accessories and connection to the test sample of a PD detection circuit (IEC60270).
3. HV energizing of the full size setup and PD detection using both systems: IEC60270 and RF PD detection system.
4. Analysis of responses of both PD detection systems: RF response of different sensors and PD occurrence e.g. PD level in [pC].
5. For PD defect from steps (1) and (3) ratio estimation of the lowest [pC] reading and [μV] for different VHF/UHF frequencies, figure 5.25.
6. Search for an artificial voltage pulse with similar frequency/amplitude characteristics as the PD defect from steps (1) and (3), figure 5.26.



a)



b)

Fig. 5.26: Example of injection of artificial pulses to simulate discharge activity:
a) 53 V to simulate 500 pC
b) 3.6 V to simulate 40 pC

Internal	**S1**	**S2**	**S3**
Range	<6MHz - 25MHz>	<6MHz - 25MHz>	<3MHz - 40MHz>
	<80MHz - 120MHz>	<70MHz - 90MHz>	<60MHz - 100MHz>
	<155MHz - 180MHz>	<110MHz - 170MHz>	<120MHz - 170MHz>
	<270MHz - 320MHz>	<220MHz - 275MHz>	
		<285MHz - 300MHz>	
		<310MHz - 320MHz>	
External	**S1**	**S2**	**S3**
Range	<3MHz - 20MHz>	<20MHz - 30MHz>	<3MHz - 40MHz>
	<70MHz - 130MHz>	<95MHz - 120MHz>	<60MHz - 80MHz>
	<180MHz - 210MHz>	<250MHz - 300MHz>	
	<250MHz - 270MHz>		

Fig. 5.27: Example of comparison of sensitivity ranges for two types of sensors: internal, external as used for sensitivity check of laboratory set-up as shown in figure 5.24.

On-site procedure

1. Performance check (sensitivity check) of the whole system: cable system, RF PD detection system including installed sensors by injection of the by (5) selected artificial voltage pulses;

2. Tuning of the unconventional PD system to HF/VHF frequency range with best signal/noise ratio;
3. Estimation of the whole circuit sensitivity in [pC], see figure 5.27;
4. Optional using IEC60270 standard calibrator injection on the cable termination of PD pulses and estimation of the RF detector responses at frequencies (e.g. below 20MHz) which are typical for TDR analysis of PD pulses in power cables.

In the following sections, examples are presented.

5.5.1 Laboratory test

To perform the laboratory test in case of power cables, a laboratory setup as shown in figure 5.24 can be used. The setup should contain: a cable length of some tens of meters; two terminations, of which one is permanently installed and should be PD free; at least one joint.

To create artificial defects, the second termination and the joint(s) will be installed in such a way that they are relatively easy to be removed. As a result, artificial defects can be inserted in these accessories, giving partial discharge activity after energizing the cable system. Moreover, internal and external PD sensors will be installed in order to collect the RF-signals coming from these PD sources.

Example of a laboratory test
As described before, to create a critical defect in a cable termination or joint is a destructive action, unless a specially designed test setup is being used. Another option is to connect an external PD source to the termination and to inject in this way partial discharges into the cable system. Figure 5.29 shows a scheme for that purpose. In this example the external PD source was a protrusion in SF_6 which was connected to generate partial discharge activity of low magnitude and high frequency content. The discharge activity is detected at the sensor, which is located just below the cable termination, see figure 5.29.

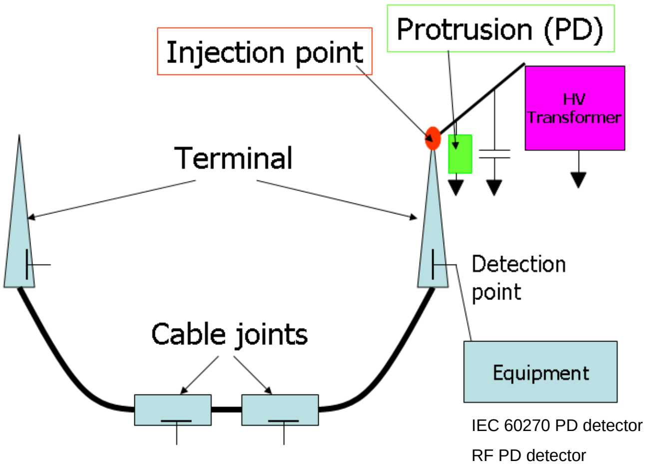


Fig. 5.28: Step 1 of laboratory test: discharging defect connected to cable termination.

In the second step of the laboratory test, a pulse generator was used to inject pulses at the cable termination while measuring with the VHF/UHF sensor placed at the grounding of the cable; different attenuator values were used to get different amplitude levels in order to check the sensitivity of the technique at lower values, see figures 5.30 and 5.31.
All comparisons were performed at the same center frequency. The PD amplitude was determined using the IEC 60270 measuring technique, which was connected and operated simultaneously with the VHF/UHF PD measurements. The results

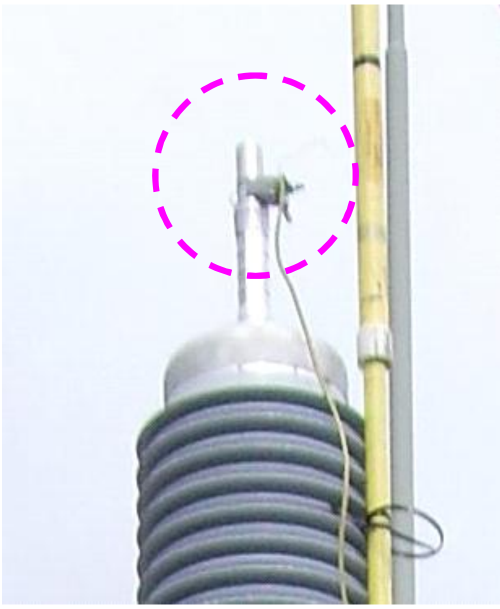
a)  b) 

Fig. 5.29: a) internal sensor close to cable termination; b) connecting artificial pulse generator to the termination;

are shown in Fig. 5.26; the recorded pulses of 53V from the pulse generator (blue) match in amplitude with the max peak of the PD pattern (red line) of 500pC at the second half cycle. The voltage level of 3.6V matches the PD level of 40pC at the first half cycle. Thus 1V represents 10pC.
Based on these laboratory experiments, a relation of 1V and 10 pC could be concluded for this configuration.

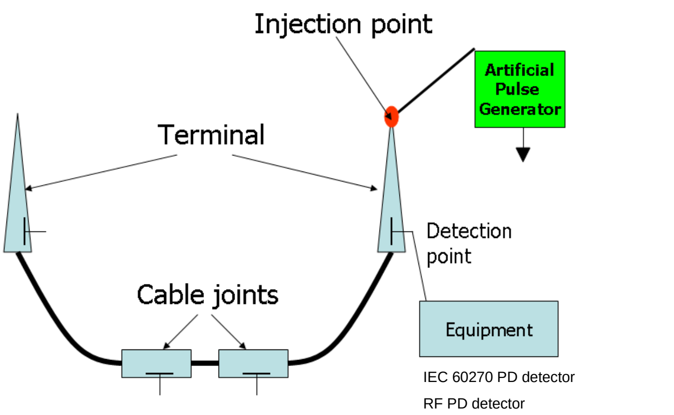


Fig. 5.30: Step 2 of laboratory test: injecting artificial pulses at termination to simulate discharging.

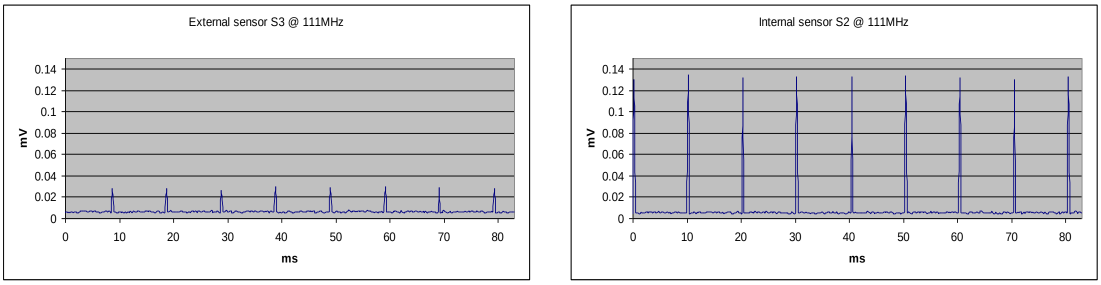
5.5.2 On-site test

The artificial pulse generator was attached at the termination as it was described before and pulses of different pC levels are injected. Based on the response of the PD detection circuit the results of the performance check will be known.
In addition to testing the whole setup including the test object, the sensor connectivity as well as measuring the background noise of the whole circuit, using IEC60270 standard calibrator artificial PD pulses can be injected on one of the cable termination and using suitable RF bandwidth (typical up to 20 MHz) the response of the particular sensor can be tested.
The results are shown in figure 5.32 which is the average frequency responses of twelve 380 kV cable terminations of the same type. It is to be noted that the frequency response is not identical for the 12 terminations and that the reasons for this are:

External sensor

Calibration pulses @ 111MHz

Internal sensor



External sensor

Calibration pulses @ 232MHz

Internal sensor

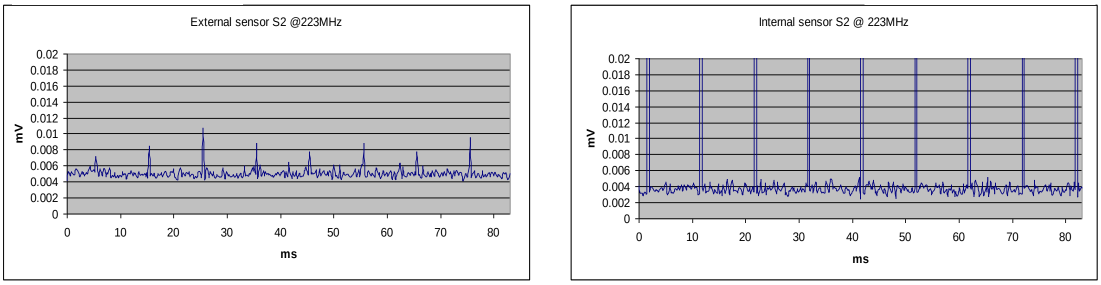


Fig. 5.31: Examples of calibration pulses as obtained using two types of sensors: internal, external at two different RF frequencies: 111 MHz and 232 MHz

1. The sensitivity check setup is prone to noise and the effects of signal attenuation and small changes can drastically affect the results. The measuring cable can be quite long, especially in the case of termination placed on a high tower. Therefore, some signal attenuation may occur in the measuring cable itself.
2. Any movement of the measuring cables causes a small change in the cable inductance, in the high-frequency characteristics of the calibration circuitry and thus in the frequency response of the total system. Slight movement of the connections of the measuring cables or any other mechanical change of the position of the measuring cable has an impact on the results of the sensitivity check.

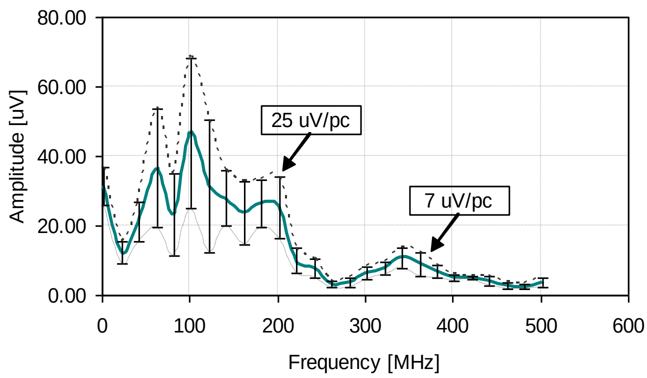


Fig. 5.32: Example of an average frequency response of twelve cable terminations to artificial pulses representing a PD activity of 20 pC.

In addition to testing the whole test-object setup, the connectivity of all installed sensors as well as the actual background noise of the whole circuit (using IEC60270 standard calibrator), artificial PD pulses can be injected on one of the cable termination and using suitable RF bandwidth (typical up to 20 MHz) the response of the particular sensor can be tested.

Therefore the following aspects should be taken into account when using measuring cables during the sensitivity check:

1. Measuring cables should not be bent, twisted or otherwise shaped without changing their characteristic impedance;
2. Measuring cables should also not run along or attached to any metallic body, because the electromagnetic field produced by the measuring signal around the cable will induce currents in the nearby conductors resulting in unwanted radiation and detuning of the line;
3. noise can also be induced directly into the cables as a result of the circuit shaping a single turn loop antenna, which makes it particularly susceptible to electromagnetic interference from logic circuits or other fast changing signals;
4. during a PD measurement in the proximity of power lines or other current-carrying conductors, currents are induced in the cables' outer shield.

These issues emerge from the fact that the electromagnetic waves propagating in open wires extend into the space surrounding the parallel wires [5.5]. In order to diminish the external noise N-type coaxial cables can be used /recommended. However, they are still subject to limits, since in practice, changes in their position will still alter results at highest frequencies.

5.5.3 Concluding remarks

The examples presented in this section show that the sensitivity check technique is very important and it can be applied for cable systems, in particular at terminations and joints. In this way a relation between the detected RF signal in mV and the sensitivity level in [pC] can be obtained.

When performing the sensitivity check for the RF PD detection system for cable systems the following factors should be considered:

1. Type, material and length of test cable and measuring cables
2. External noise (eventual presence of noise sources in the proximity of the test objects, e.g. antennas, power electronic devices, etc.)
3. Positioning and handling of measuring cables

From the obtained results it can be seen that depending on these factors the transfer function of each component (especially at the higher frequencies, which are generally the most important for this measuring technique) is different at different measuring frequencies. Therefore sufficient experience is required when performing the sensitivity check, in order to obtain reproducible results.

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