Chapter 17

Partial discharge measuring technique

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17.1 Introduction

A partial discharge (PD) is a localised electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor. This definition is given in IEC Publication IEC 60270 Ed. 2, 2000 [1], which is the revision of IEC Publication 60270 [2]. Partial discharges are in general a consequence of local electrical stress in the insulation or on the surface of the insulation. The discharges normally appear as pulses with a duration of less than 1 μs. So-called continuous pulseless discharges in gaseous dielectrics also exist, but this kind of discharge will not be handled in this chapter. Furthermore, the term 'corona' is often used for the partial discharges that occur in gaseous media around conductors which are remote from solid or liquid insulation, and therefore 'corona' is a particular kind of partial discharge.

Partial discharges are a sensitive measure of local electrical stress and therefore the measurement is very often used as a quality check of the insulation. The inception of partial discharges gives information on the limit of the electrical strength of the insulating material before a complete discharge between the conductors takes place. Therefore the insulating material can be tested with high stress but without damaging or reducing the performance of the insulation. Also, for partial discharge measurements it should be taken into account that every stress of the insulation will have an influence on the life expectancy of the material, but a reasonable compromise between the stress during the measurement in order to get reliable results and the influence of the lifetime should be found and established in the relevant standards for the particular equipment, e.g. transformers, cables, switchgears, etc.

The partial discharge measurement is a typical nondestructive test and it can be used to judge the insulation performance at the beginning of its service time taking into account the reduction of the performance during the service time by the ageing, whereby the ageing depends on numerous parameters like electrical stress, thermal stress and mechanical stress. Depending on the kind of insulating material, different limits for the allowed partial discharge value at a given stress are defined in the relevant recommendations. In particular, for solid insulation where a complete breakdown seriously damages the test object the partial discharge measurement is a tool for quality assessment.

17.2 Physical background of partial discharges

Partial discharges occur at locations where the electrical stress exceeds the limit of the insulating material. These limits depend on different parameters like kind of material, temperature, pressure, duration of stress, purity, etc. In any case the inception of partial discharges at a given applied voltage demonstrates that at least locally a strength limit has been reached. Depending on the insulating material the voltage level at which partial discharges occur and the amount of charges allow evaluation of the performance and quality of the insulation to be tested based on experimental values. The most critical type of insulation is solid material, and therefore the examples are based on that. The partial discharge measurement on a solid insulation should demonstrate that under a given stress the insulation will withstand the service conditions for, for example, 30 years. It is therefore necessary to know the change of performance due to ageing under the service conditions. Figure 17.1 shows a simplified diagram of the electrical performance of a solid insulating material as a function of the service time/period of stress.

The electrical breakdown takes place at the beginning of the period of stress, followed by the so-called thermal breakdown and the later erosion

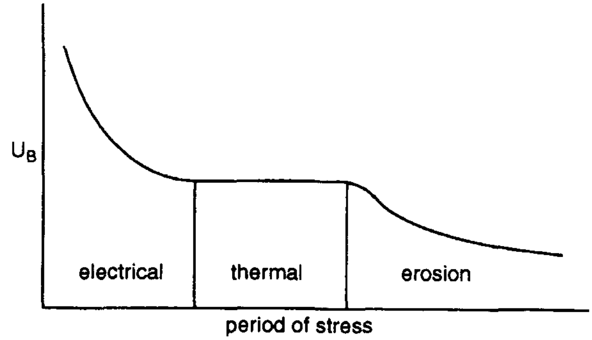

Figure 17.1 Breakdown voltage as function of the period of stress

breakdown, mainly caused by partial discharges which need a long time until complete discharge between the two conductors occurs. It should be noted that the time axis in Figure 17.2 is not linear due to the different time ranges for the different types of breakdown. For high voltage equipment, very often insulating materials are used where the area of thermal breakdown does not exist because the power losses are very small. For these materials the breakdown voltage behaviour as a function of time/period of stress is shown in Figure 17.3.

There is no clear separation between the electrical and erosion breakdown, and experience shows that this curve can be described by the so-called lifetime law,

$$E^N t = \text{const.} \tag{17.1}$$

where E is electrical field strength, N is the lifetime coefficient and t is period of stress.

The effect of volume on the breakdown strength of solid material can also be taken into account by modification of this equation. The strength of this equation is the fact that with reasonable voltage period of stress an estimation of the expected lifetime can be made and that a partial discharge measurement at the beginning of the period of stress gives reliable information concerning the behaviour of the material in the time range where complete breakdown is caused by erosion.

The detection and measurement of partial discharges is based on the assumption that in the insulating material small cavities exist in which the discharge takes place. This discharge causes a charge transfer in the whole circuit by an impulse shaped current which can be detected and measured. The relation of the discharge event and the phase angle of the applied voltage at power frequency is also important for measurement of the partial discharge because the nature of the defect can be determined.

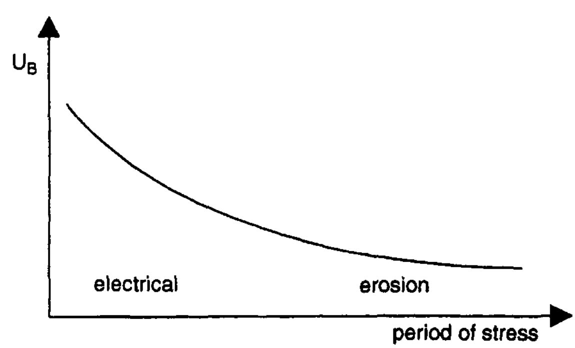

Figure 17.2 Breakdown voltage as function of period of stress for insulating material with very low power losses

In Figure 17.3 a simplified equivalent circuit for the explanation of the partial discharges is shown.

The voltage across the capacitor C_1 is given by the following equation:

$$U_1 = U\frac{C_1}{C_1 + C_2} \tag{17.2}$$

The discharge of the spark gap S represents the partial discharge, and this takes place when the voltage U_1 has reached the so-called inception level of partial discharges. Under ideal conditions the discharge process of the spark gap S needs no time, but for real arrangements the discharge process is still very fast and can be neglected in regard to the timescale of the applied voltage. Owing to the discharge of the capacitor C_1 the capacitor C_2 is now stressed with the voltage U, and this causes a change in the charges. Before the breakdown of the spark gap S the charge Q_2 of the capacitor C_2 is

$$Q_2 = U_2C_2 = U\frac{C_1C_2}{C_1 + C_2} \tag{17.3}$$

After the breakdown the charge Q_2* is

$$Q_2{}^* = UC_2 \tag{17.4}$$

The charge difference should be delivered by the capacitor C_3 or by the voltage source. Because of the different time constants the charge will be delivered by the capacitor C_3 in a very short current pulse. This current pulse causes a reduction in the voltage across the capacitors C_2 and C_3, so

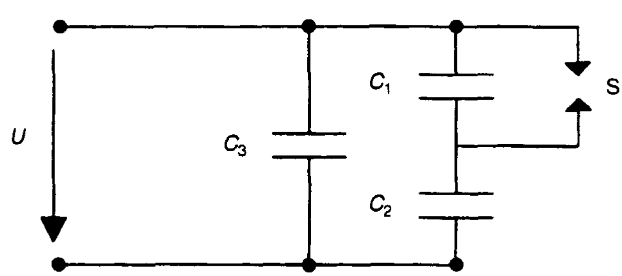

Figure 17.3 *Equivalent circuit for the partial discharges*
U = applied voltage at power frequency
C_1 = capacitor representing the cavity
C_2 = capacitor representing insulating material around cavity
C_3 = capacitor representing remaining insulating material
S = spark gap representing discharge of capacitor C_1

the power supply reacts and the voltage will be increased up to the original value U by charging all the capacitors. More or less at the same time the spark gap S has been recovered and the capacitor C_1 will be charged again until it reaches the breakdown voltage of the spark gap S. The charge difference can be calculated according to the equation

$$\Delta Q = U \frac{C_1^2}{C_1 + C_2} \tag{17.5}$$

Because neither C_1 nor C_2 is known, only the short current pulse through a coupling device or an impedance can be measured. Therefore the capacitor C_3 is normally replaced by a coupling capacitor C_k as shown in Figure 17.4, where the capacitor C_a represents the whole capacitor arrangement of Figure 17.3.

The partial discharge (resp. the discharge) of capacitor C_1 causes an impulse current flowing in the circuit given by the test object C_a, the coupling capacitor C_k and the coupling device CD (resp. the impedance Z_{mi}). The integration of this current gives the measured charge. This circuit is normally known as a parallel coupling circuit because the coupling capacitor and the test object are connected in parallel. From the measuring point of view it makes no difference if the coupling device is in series with the test object C_a, but in this case the test object should be isolated from ground, and this is very often not possible.

The most important aspect of partial discharge measurement is the calibration. Normally only the terminals of the test object are accessible, and the charge which can be measured there is defined as the apparent

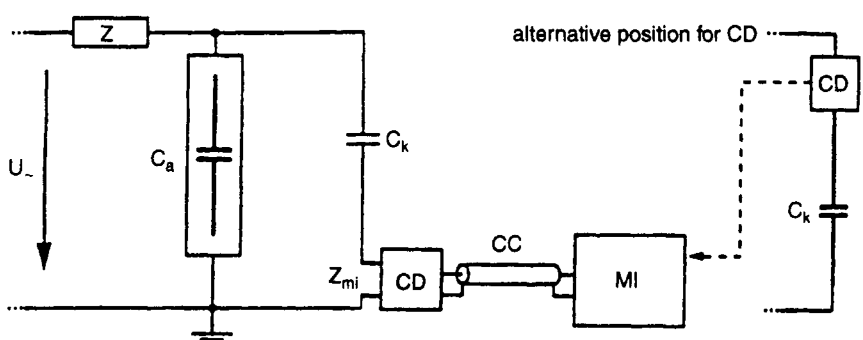

Figure 17.4 Basic partial discharge measurement circuit
$U_\sim$ = high voltage supply, Z_{mi} = input impedance of measuring system, C_c = connecting cables, C_a = test object (C_1, C_2 and C_3 of Figure 17.3), C_k = coupling capacitor, CD = coupling device, MI = measuring instrument, Z = high voltage filter

charge q according to IEC Publication 60270 Ed. 2, 2000 [1]. A partial discharge pulse with a unipolar charge q, injected at the terminals of the test object in the specified test circuit within a very short time, would give the same reading on the measuring instrument as the partial discharge pulse in the insulation material itself. The apparent charge is usually expressed in picocoulombs (pC). It is clear that the measured apparent charge is not equal to the amount of charge locally involved at the discharge of the capacitor C_1 in Figure 17.3, and there is no more information on the amount of charge available as it can be measured on the accessible terminals of the test object.

The relationship between the occurrence of partial discharges and the phase of the applied voltage depends on the type of defect. Assuming a sharp point at the high voltage electrode of an air insulated arrangement, the partial discharges start when the voltage at the sharp point reaches the negative peak value due to the behaviour of the electrons. With an increase in voltage the partial discharges also occur at positive peak value. Therefore the location of a sharp point generating partial discharges is simple. More complicated is the situation in solid materials where small cavities (capacitor C_1 in Figure 17.3), discharge (breakdown of spark gap S in Figure 17.3) and the pulses are measured in a test circuit according to Figure 17.4. Figure 17.5 shows the typical partial discharge behaviour of a solid material assuming that the discharge voltage is constant and polarity independent and that the former breakdowns do not influence the breakdown voltage of the cavity.

It can be seen that in this case the partial discharge occurs around the zero crossing point of the applied voltage, which is completely different from partial discharges in air. The number of pulses depends on the breakdown voltage of the cavity and may be different for the two polarities in real insulating arrangements. Furthermore, the amount of charge is also not constant for all pulses and therefore some other important parameters should be measured or calculated.

17.3 Requirements on a partial discharge measuring system

The most important parameter of the partial discharge measurements is the apparent charge q, because this value gives a reference for the specified test circuit and test object after calibration. Because of the randomness of the partial discharges, averaging of the measured pulses by the recording device is necessary to prevent wrong measurement from only a single event. This is in particular important under real measuring conditions where a number of different noise sources influences the partial discharge measurement. The pulse repetition rate n is given by the number of partial discharge pulses recorded in a selected time interval and the duration of this time interval. The recorded pulses should be above a

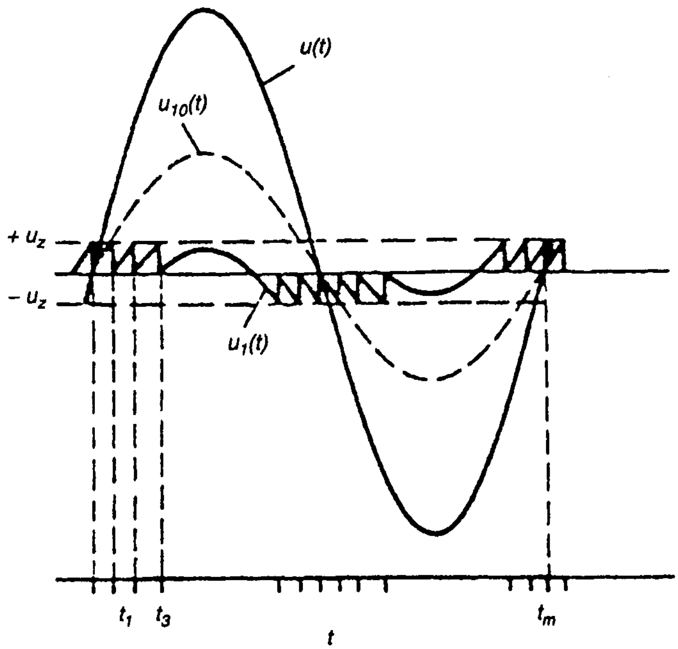

Figure 17.5 *Partial discharge behaviour of solid insulating material*
$u(t)$ = applied voltage at power frequency
$u_{i0}(t)$ = voltage across capacitor C_i without partial discharges
$u_i(t)$ = voltage across capacitor C_i with partial discharges
u_z = partial discharge onset voltage
t_i = partial discharge occurrence time

certain limit, depending on the measuring system as well as on the noise level during the measurement. The pulse repetition frequency N is the number of partial discharge pulses per second in the case of equidistant pulses. Furthermore, the phase angle Φ_i and the time of occurrence t_i are information on the partial discharge pulse in relation to the phase angle or time of the applied voltage with period T:

$$\Phi_i = 360\,(t_i/T) \tag{17.6}$$

The reference point is the positive going transition of the applied voltage.

The interpretation of the partial discharge measurements frequently requires further derived quantities like discharge power P, quadratic rate D and average discharge current I, which are described in detail in Reference 1.

For measurement purposes the largest repeatedly occurring partial discharge magnitude and the specified partial discharge magnitude are also important. For partial discharge measurements with voltage at power frequency the specified magnitude of the apparent charge q is the largest repeatedly occurring partial discharge magnitude.

The performance of an insulating material can also be evaluated by the partial discharge inception voltage U_i and the extinction voltage U_e. The inception voltage is the applied voltage at which repetitive partial discharges are first observed when the voltage is gradually increased from a lower level where no partial discharges occur. The extinction voltage is the applied voltage at which repetitive partial discharges cease to occur when the voltage is gradually reduced from a higher level at which partial discharges are observed. This value is in practice the voltage level at which the specified magnitude of partial discharges is below the specified low value or the limit of the recording system.

For reference measurements a partial discharge test voltage level is specified as a voltage level at which the test object should not exhibit partial discharges exceeding the specified partial discharge magnitude applied in a specified partial discharge test procedure.

Because of the numerous noise sources the partial discharge measurement should be carried out in a frequency range where the noise is as low as possible. The short and small current impulses should not be disturbed by the power frequency or its harmonics. Therefore a lower and upper frequency limit should be defined at which the transfer characteristic of the coupling device has fallen by 6 dB from the peak passband value. The measurement of a partial discharge pulse is an integration of the current over the time, and the transformation from the time to the frequency domain means that the charge of a pulse is given by the amplitude content at zero frequency. As long as the frequency response of the coupling device and moreover of the complete measuring system is flat, the information concerning the charge of a pulse can be taken at any frequency. However, the noise reduction may be more efficient in a certain frequency range and therefore the frequency response of the measuring system should be appropriate. Figure 17.6 shows an example of a characteristic frequency response.

The midband frequency f_m and the bandwidth f are given by the following equations:

$$f_m = \frac{f_1 + f_2}{2} \tag{17.7}$$

$$\Delta f = f_2 - f_1 \tag{17.8}$$

The characterisation of the measuring circuit concerning the frequency range is done by its transfer impedance $Z(f)$, which gives the ratio of the

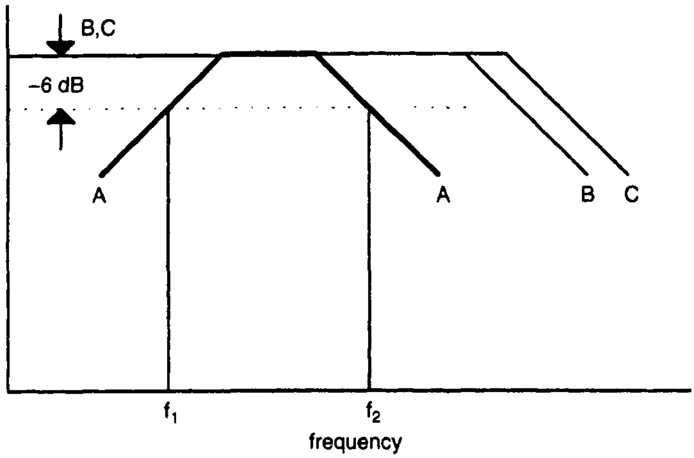

Figure 17.6 *Frequency response of a measuring system and pulses*
A = bandpass of the measuring system
B = frequency spectrum of the partial discharge pulse
C = frequency spectrum of a calibration pulse
f_l *= lower frequency limit*
f_2 *= upper frequency limit*

output signal amplitude to a constant input signal amplitude as a function of the frequency assuming that the input signal is sinusoidal.

The pulse resolution time T_r is the shortest time interval between two consecutive pulses of short duration, same shape, polarity and charge magnitude for which the response will not change by more than 10% of that for a single pulse. The pulse resolution is in general inversely proportional to the bandwidth Δf.

17.4 Measuring systems for apparent charge

It is recommended in [1] that the relevant Technical Committees should use the apparent charge as the quantity to be measured and that the test circuit and the measuring system shall be calibrated. To measure the possible partial discharges within the test object it is necessary that the complete test circuit is 'free' of partial discharges, which means that the level of partial discharges within the test circuit is below the required partial discharge magnitude at the relevant applied voltage level. This needs proper design of the test equipment, the high voltage connections and the grounding of all apparatus in the vicinity of the test circuit. Furthermore, very sensitive measurements require shielding of the whole test arrangement against electromagnetic interferences.

The coupling device is normally a passive four-terminal network which converts the current pulse to a voltage signal, and its frequency response is chosen to prevent the power frequency and its harmonics from the recording instrument.

Generally the response of the recording system is a voltage pulse where the peak value is proportional to the charge of the current impulse. The shape, duration and peak value of the voltage pulse are determined by the transfer behaviour of the measuring system, and shape and duration may be completely different from the original current pulse. To get a reasonable measurement, integration of the recorded pulses should be done in such a way that the indication of the largest repeatedly occurring partial discharge magnitude is according to Table 17.1 for equally large equidistant pulses of a given charge.

This characteristic is necessary to get the same readings with different types of instruments, including digital recording systems, and to establish compatibility of partial discharge measurements.

Regarding the frequency range, two types of systems exist: wideband and narrowband partial discharge measuring systems. The recommended values for a wideband system according to [1] are:

$$30\ \text{kHz} < f_1 \leqslant 100\ \text{kHz}$$
$$f_2 \leqslant 500\ \text{kHz}$$
$$100\ \text{kHz} \leqslant \Delta f \leqslant 400\ \text{kHz}$$

The response of such a system to a partial discharge current pulse is in general a well damped oscillation. The apparent charge q and the polarity of the partial discharge pulse can be determined, and the pulse resolution time T_r is small, typically in the range of 5–20 μs.

Narrowband measurements are characterised by a small bandwidth Δf and a midband frequency f_m. Recommended values are

$$9\ \text{kHz} \leqslant \Delta f \leqslant 30\ \text{kHz}$$
$$50\ \text{kHz} \leqslant f_m \leqslant 1\ \text{MHz}$$

The response of such a system to a partial discharge current pulse is a transient oscillation with the negative and positive peak value of its envelope proportional to the apparent charge q independent of the polarity of this charge. The pulse resolution time T_r is large and typically >80 μs.

Table 17.1 Reading R in % as function of the pulse repetition rate N

N, 1/s	1	2	5	10	50	≥ 100
R_{min}, %	35	55	76	85	94	95
R_{max}, %	45	65	86	95	104	105

17.5 Calibration of a partial discharge measuring system

The aim of the calibration is to verify that the measurement system is able to measure the specified partial discharge magnitude correctly. With the calibration of the measurement system within the complete test circuit the scale factor for the measurement of the apparent charge q will be determined. Because of the influence of the test object the calibration shall be made with each new test object.

The calibration is carried out by injecting a short duration pulse of known charge magnitude q_0 into the terminals of the test object. The reading of the instrument at this given charge can then be adjusted in order to have a reasonable scale factor for the later partial discharge measurements. The calibration should be done for each measuring range used.

The calibration pulses are generally derived from a calibrator producing a voltage step of the amplitude U_0 in series with a capacitor C_0 so that the repetitive charges have the magnitude

$$q_0 = U_0 C_0$$

The rise-time of the voltage step shall be very small, $\leqslant$60 ns. The detailed requirements on the calibrator as well as on the procedure are described in Reference 1.

17.6 Examples of partial discharge measurements

The relevant Technical Committees should specify the minimum measurable magnitude required for the apparatus [3–5]. To obtain reproducible results in partial discharge measurements careful control of all relevant factors is necessary, e.g. the surface of the external insulation of the test object shall be clean and dry because moisture or contamination on insulating surfaces may cause partial discharge at the required test voltage and then internal partial discharge cannot be detected. Normally the partial discharge magnitude is determined at a specified test voltage. If this magnitude is below the required value the test object has passed the test. Very often the partial discharge inception and extinction voltage are of interest. Then the voltage has to be increased and decreased according to the recommendations. These tests are simple if the background noise is low enough to permit a sufficient and accurate measurement, which is the case in well shielded high voltage laboratories. If the measurements should be carried out on-site under normally very noisy conditions, then more sophisticated measuring systems should be used and also more effort in data processing may be necessary.

17.6.1 Partial discharge measurement on high voltage transformers

The partial discharge measurement of a transformer on-site requires, in any case, the suppression of different kinds of noises. The partial discharge sensors may be capacitors or Rogowski coils, depending on the actual situation and the purpose of measurement. Figure 17.7 shows the original measured signal during a partial discharge measurement on a transformer. Only after the filtering of sinusoidal noise can the partial discharge pulses be recognised, including the calibration signal at 60 ms.

The filtered signal still has too high a noise level, and therefore further filtering methods reducing the synchronous noise are necessary. The impulse shaped noise remains because the signal does not differ from the true partial discharge signal and therefore the signal direction may be used for the separation between noise and partial discharge signal, as shown in Figure 17.8.

17.6.2 Partial discharge measurement and location on high voltage cables

The partial discharge measurement on high voltage cables requires a low background noise, because the specified partial discharge magnitude for XLPE cables is very low. Already the partial discharge measurements within the factory are not simple because special cable terminations are necessary which are free of partial discharge at the test voltage. With the appropriate equipment and test conditions (shielded laboratory) the required low background noise can be reached. On-site partial discharge measurements are more critical and the lowest detectable partial discharge magnitude in the test object is higher than in the factory. Data

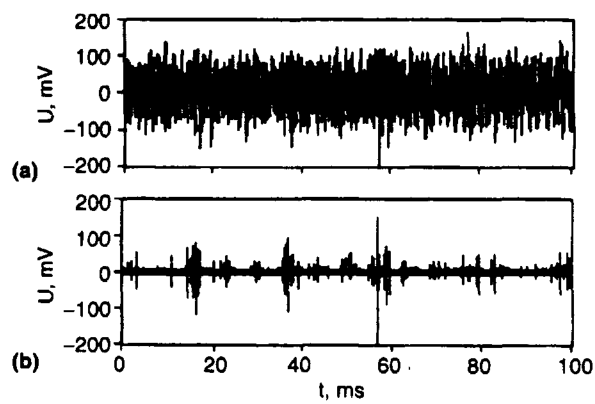

Figure 17.7 Partial discharge measuring signal without **(a)** *and with* **(b)** *filtering of sinusoidal noise*

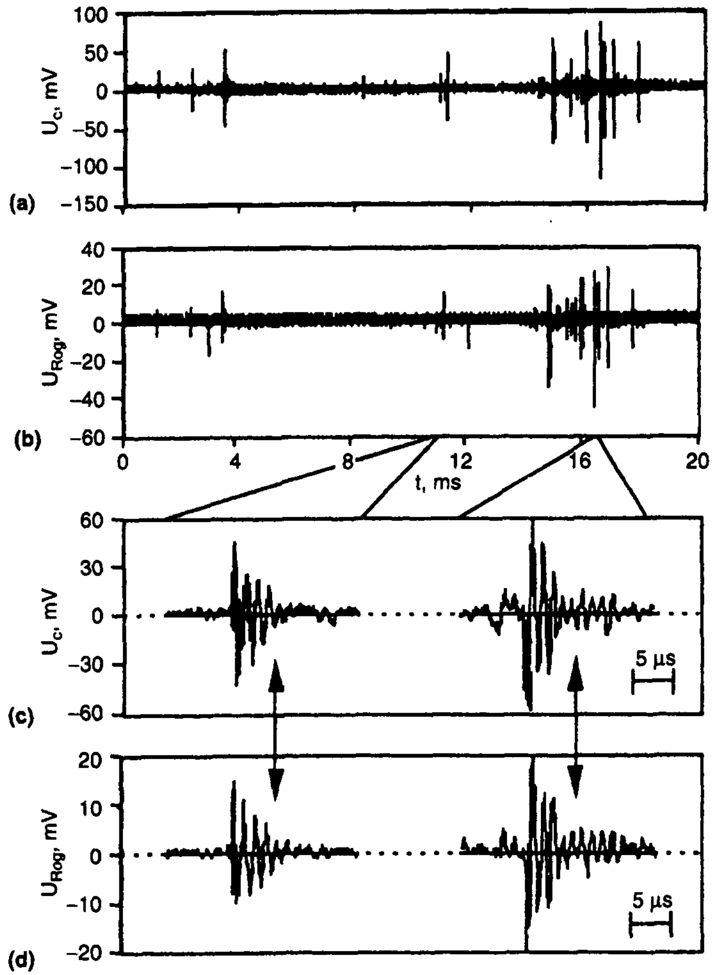

Figure 17.8 *Partial discharge measuring signal after filtering of sinusoidal and synchronous noise* (**a, b**) *and with additional filtering of impulse shaped noise* (**c, d**) *by detection of the signal direction*
U_c = output of the capacitive coupling unit
U_{Rog} = output of the Rogowski coil

processing can reduce the noise level, and the particular behaviour of the cable (travelling waves) allows the location of the partial discharge within the cable length. Figure 17.9 shows the result of a partial discharge measurement on a high voltage cable on-site. The sensor is a Rogowski coil mounted on one cable termination. From the digital record the travelling time of the original signal τ as well as the reflected signal, at the opposite end of the cable, τ_r of a single partial discharge can be evaluated. With

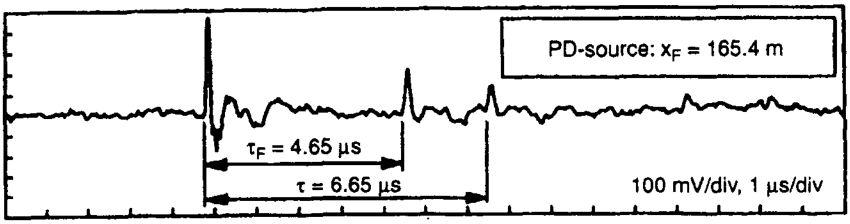

Figure 17.9 Partial discharge measurement and location on a cable on-site

the known length of the cable the location of the partial discharge can be calculated.

17.6.3 Partial discharge measurement on high voltage gas insulated substations

Gas-insulated substations and their components are tested within the factory, and this includes partial discharge measurements on the insulating parts and the complete equipment. Anyhow, some assembly work is necessary on-site and therefore a voltage test with AC including partial discharge measurement is the most reliable test to detect weak points concerning the electrical behaviour. Because of the problem of the high noise level on-site, partial discharge measurement at ultra high frequencies (UHF) seems to be the most sensitive method. The conventional partial discharge method already described can also be used, but the very low value of the apparent charge for a typical failure in a gas-insulated substation, a needle on the high voltage electrode, may be not detectable with this method. Therefore the example shows the result of a partial discharge measurement of a typical gas-insulated substation arrangement [6]. Figure 17.10 shows the test set-up with the position of the failure (free moving particle) and of the different UHF partial discharge sensors.

Figure 17.11 shows the measured signal at different positions to show the strong dependence of the signal amplitude on the distance between the failure and the sensor position and to demonstrate the high sensitivity of this method.

The partial discharge signal can still be detected at S8, which is ~20 m from the failure position. The only disadvantage of this method is the fact, that the measurement cannot be calibrated according to the relevant IEC Publication [1], but the sensitivity can easily be checked according to a proposal by the CIGRE [7]. With this sensitivity check it can be assumed that no defects with a partial discharge level above the given value exist within the tests of the gas-insulated substation, and this information is the most important for the evaluation of the on-site tests.

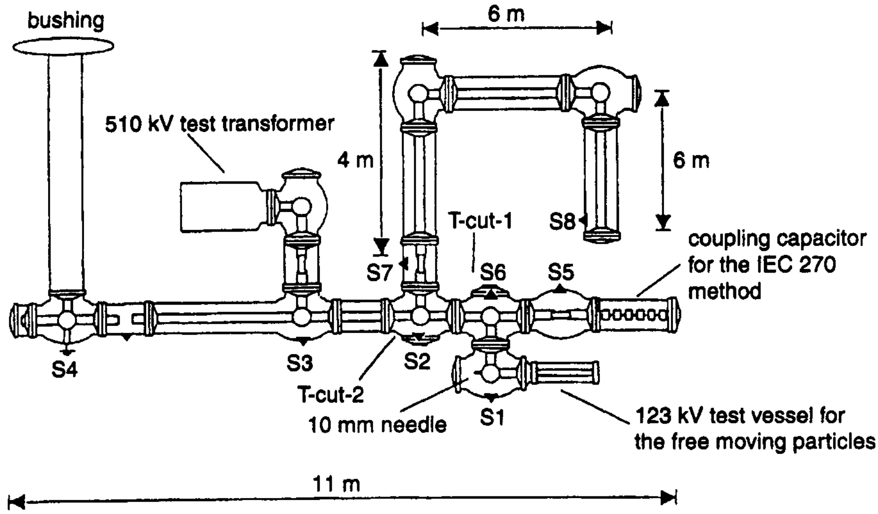

Figure 17.10 Set-up for a UHF partial discharge measurement on a gas insulated substation

17.7 Conclusions

1. Partial discharge measurement is a very sensitive tool for quality checking of insulating materials.
2. The measurement of the apparent charge is a relative measurement and requires the reference values given by the Standards and based on practical experience.
3. The main problem of partial discharge measurements is the separation between noise and partial discharge signals, but with proper selection of the bandwidth and the use of intelligent procedures like filtering the measurements can also be carried out under on-site conditions.
4. The examples of partial discharge measurements on high voltage cables, transformers and gas-insulated substations demonstrate the benefit of the partial discharge measuring technique.

17.8 References

1 IEC Publication 60270, Ed. 3.0. 'High-voltage test techniques – Partial discharge measurement', Ed. 2, 2000
2 IEC Publication 60270. 'Partial discharge measurement', 1981
3 IEC Publication 60076–3. 'Power transformers – Part 3: Insulation levels and dielectric tests', 1980

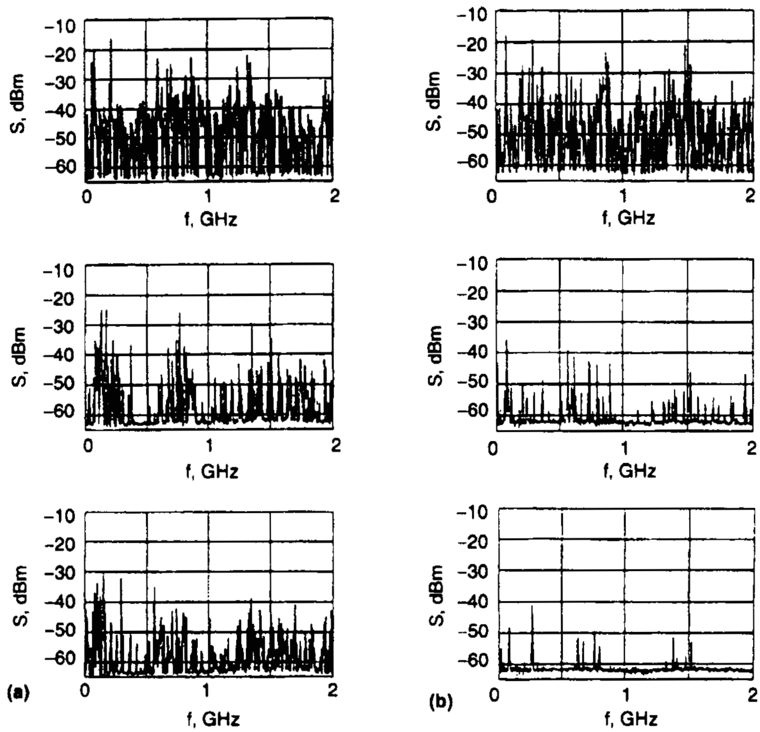

Figure 17.11 *Partial discharge signals at different sensors*
(a) *Partial discharge of a 10 mm free moving particle measured at S1, S3 and S4 (top to bottom)*
(b) *Partial discharge of a 5 mm free moving particle measured at S1, S4 and S8 (top to bottom)*

4 IEC Publication 60840. 'Power cables with extruded insulation and their accessories for rated voltages above 30 kV up to 150 kV – Test methods and requirements', 1999

5 IEC Publication 60517. 'Gas-insulated metal-enclosed switchgear for rated voltage of 72.5 kV and above', 1990

6 KURRER, R. and FESER, K. 'Attenuation measurements of ultra-high-frequency partial discharge signals in gas-insulated substations'. 10th Int. sympos. on *High voltage engineering*, Montreal, 1997, pp. 161–164

7 BOECK, W. *et al.*: 'Sensitivity verification for partial discharge detection systems for GIS with the UHF method and the acoustic method', *Electra*, April 1999, **183**, pp. 75–87