Chapter-2

Fundamental of Partial Discharge & Measuring Methods
2.1 BASIC PD EQUIVALENT CIRCUIT\textsuperscript{[2]}

For the evaluation of the fundamental quantities related to a PD pulse, simulation of the test object is carried out by the simple capacitor arrangement. Figure-2.1(a) shows solid or fluid dielectric materials between the two electrodes or terminals A and B, and a gas-filled cavity.

The electric field distribution within this test object is simulated by partial capacitance, which is possible as long as no space charges disturb this distribution. Electric field lines within the cavity are represented by $C_c$ and those starting or ending at the cavity walls form the two capacitances $C_b'$ and $C_b''$ within the solid or fluid dielectric. All field lines outside the cavity are represented by $C_a = C_a' + C_a''$. Due to realistic geometric dimensions involved, and as $C_b = \frac{C_b'C_b''}{C_b + C_b''}$ the magnitude of the capacitances will then be controlled by the inequality

$$C_a > C_c > C_b$$ \hspace{2cm} \text{... (2.1)}

![Figure-2.1 Simulation of a PD test objects](image)

(a) Scheme of an insulation system comprising a cavity. (b) Equivalent circuit
This void will become the origin of a PD if the applied voltage is increased and the field gradients in the void are strongly enhanced by the difference in permittivity as well as by the shape of the cavity. For an increased value of an A.C. voltage, the discharge will appear first at the crest or rising part of a half-cycle. This gas discharge creates electrons as well as negative and positive ions, which are driven to the surfaces of the void. It forms dipoles or additional polarization of the test object. This physical effect reduces the voltage across the void significantly. Within the model these effect causes the cavity capacitance $C_c$ to discharge largely. If the voltage still increase or decrease by the negative slope of an A.C. voltage, new field lines are built up and hence the discharge phenomena is repeated during each cycle. If increased D.C. voltages are applied then one or only a few partial discharges will occur during the rising part of the voltage. In case of constant voltage, the discharges will stop as long as the surface charges deposited on the walls of the void do not recombine or diffuse into the surrounding dielectric.

This phenomenon is simulated by the equivalent circuit that is shown in Figure-2.1(b). Here, the switch $S$ is controlled by the voltage $V_c$ across the void capacitance $C_c$, and $S$ is closed only for a short time, during which the flow of a current $i_c(t)$ takes place. The discharge current $i_c(t)$, which cannot be measured, would have a shape as governed by the gas discharge process and would in general be similar to a Dirac function, i.e. this discharge current is generally of a very short pulse in the nanosecond range.

It is assumed that the sample was charged to the voltage $V_a$ but the terminals A and B are no longer connected to a voltage source. If the switch $S$ is closed and $C_c$ becomes completely discharged then the current $i_c(t)$ releases a charge $\delta q_c = C_c \delta V_c$ from $C_c$, a charge which is lost in the whole system, assumed for simulation. By comparing the charges within the system pre and post discharge, it is derived that the voltage drop across the terminal is
\[
\delta V_a = \left\{ \frac{C_b}{(C_a + C_b)} \right\} \times \delta V_c \tag{2.2}
\]

This voltage drop contains no information about the charge $\delta q_c$, but it is proportional to $C_b \delta V_c$, a magnitude related to this charge, where $C_b$ increases with the geometric dimensions of the cavity.

$\delta V_a$ is clearly a quantity that could be measured. It is a negative voltage step with a rise time depending upon the duration of $i_c(t)$. The magnitude of the voltage step is quite small and although $\delta V_c$ is in a range of $10^2$ to $10^3$ V; but the ratio $C_b/C_a$ will always be very small according to Eq.2.1. Thus, a direct detection of this voltage by the measurement input voltage would be a tedious task. The detection circuits are based upon another quantity, which can immediately be derived from a nearly complete circuit shown in Figure-2.2.

The test object (Figure-2.1.a) is now connected to an A.C. voltage source $V$. An impedance $Z$, either comprises only the natural impedance of the lead between voltage source and the parallel arrangement of $C_k$ and $C_t$ or enlarged by a PD-free inductance or filter. It may disconnect the ‘coupling capacitor’ $C_k$ and the test specimen $C_t$ from the voltage source during the short duration PD phenomena and $C_k$ is a storage capacitor or quite a stable voltage source during the short period of the partial discharge.

![Figure-2.2 The PD test object $C_t$ within a PD test circuit](image)
It releases a charging current or the actual ‘PD current pulse’, i(t) between C_k and C_t and tries to cancel the voltage drop $\delta V_a$ across $C_t \approx (C_a + C_b)$. If $C_k >> C_t$, then $\delta V_a$ is completely compensated and the charge transfer provided by the current pulse i(t) is given by

$$q = \int i(t) = (C_a + C_b)\delta V_a$$

...(2.3)

Therefore,

$$q = C_b\delta V'_c$$

...(2.4)

Hence, it is referred as the apparent charge of a PD pulse, which is the most fundamental quantity of all PD measurements. The word ‘apparent’ was introduced because this charge again is not equal to the amount of charge locally involved at the site of the discharge or cavity C_c. This PD quantity is much more realistic than $\delta V_a$ in Eq-2.2, as the capacitance $C_a$ of the test object, which is its main part of $C_t$, has no influence on it.

In practice, the condition $C_k >> C_a (=C_t)$ is not always applicable. Here, either $C_t$ is quite large or the loading of an A.C. power supply becomes high and the cost of building such a large capacitor without PD is not economical. For a finite value of $C_k$, the charge $q$ or the current $i(t)$ is reduced, as the voltage across $C_k$ will also drop during the charge transfer. Designating this voltage drop by $\delta V_a^*$, can be computed by assuming that the same charge $C_b\delta V_c$ has to be transferred in the circuits of Figure-2.1(b) and figure-2.2. Therefore,

$$\delta V'_a(C_a + C_b) = \delta V^*(C_a + C_b + C_k)$$

...(2.5)

Using equation (2.2) and (2.4), it is obtained as
\[ \delta V^* = \frac{C_b}{C_a + C_b + C_k}, \quad \delta V_C = \frac{q}{C_a + C_b + C_k} \quad \text{...(2.6)} \]

Again, \( \delta V^* \) is a difficult quantity to be measured. The charge transferred from \( C_k \) to \( C_t \) by the reduced current \( i(t) \) is equal to \( C_k \delta V^* \). However, it is related to the real value of the apparent charge \( q \), which can be measured by an integration procedure and referred as \( q_m \) (measured quantity), then

\[ q_m = C_k \delta V^* = \frac{C_k}{C_a + C_b + C_k} q \approx \frac{C_k}{C_a + C_k} q \]

\[ \frac{q_m}{q} \approx \frac{C_k}{C_a + C_k} \approx \frac{C_k}{C_t + C_k} \quad \text{...(2.7)} \]

The relationship \( q_m/q \) indicates the difficulties arising in PD measurements for test objects of large capacitance values \( C_t \). Although \( C_k \) and \( C_t \) may be known, the ability to detect small values of \( q \) will decrease as all instruments capable of integrating the currents \( i(t) \) will have a lower limit for quantifying \( q_m \). Eq-2.7, therefore sets limits for the recording of ‘pico-coulombs’ in large test objects. During actual measurements, a calibration procedure is needed where artificial apparent charge \( q \) of well-known magnitude is injected to the test object.
2.2 The Recurrence of Discharge (Discharge Sequence) \(^{2,3}\)

In practice, a cavity in a material is often nearly spherical, and for such cases the internal field strength is

\[
E_c = \frac{3\varepsilon_r E}{\varepsilon_{rc} + 2\varepsilon_r} = \frac{3E}{2}
\]

\[\text{...(2.8)}\]

For, \(\varepsilon_r >> \varepsilon_{rc}\).

Here, \(E\) is in the average stress in the dielectric under an applied voltage \(V_a\). During the operation when \(V_c\) reaches breakdown value \(V^+\) of the gap \(t\) then the cavity may break down. The sequence of breakdown under sinusoidal alternating voltage is illustrated in Figure-2.3. The dotted curve shows the voltage which would appear across the cavity if it does not break down. As \(V_c\) reaches the value \(V^+\), a discharge takes place, the voltage \(V_c\) collapses and the gap extinguishes. The voltage across the cavity then starts increasing again until it reaches \(V^+\) when a new discharge occurs. Thus, several discharges may take place during the rising part of the applied voltage. Similarly, on decreasing the applied voltage, the cavity discharges as the voltage across it reaches \(V\). In this way, groups of discharges originate from a single cavity and give rise to positive and negative current pulses on increasing and decreasing of the voltage respectively.
When the gas in the cavity breaks down, the surface of the insulation, provide instantaneous cathode and anode. Some of the electrons impinge upon the anode are sufficiently energetic to break the chemical bonds of the insulation surface. Similarly, bombardment of the cathode by positive ions may cause damage by increasing the surface temperature and produce local thermal instability. In addition, channels and pits are formed which elongate the insulation by the ‘edge mechanism’. Additional chemical degradation may result from active discharge products, and hence the net effect is a slow erosion of the material and a consequent reduction of the breakdown strength of the solid insulation. When the discharge occurs on the insulation surface, the erosion takes place initially over a comparatively large area. The erosion roughens the surface and slowly penetrates the insulation and later on it will increase channel propagation and ‘tree-like’ growth through the insulation is formed.

For practical application, it is important that the dielectric strength of a system does not deteriorate significantly over a long period of time (years). In practice, however,
because of imperfect manufacturing and/or poor design, the dielectric strength decreases with the time of voltage application (or the life). In many cases, the decrease in dielectric strength \((E_b)\) with time \((t)\) follows the empirical relationship.

\[
tE_b^n = const \quad \ldots(2.9)
\]

Where the exponent ‘\(n\)’ is derived from the dielectric material, ambient conditions and the quality of manufacturing.
2.3 PD CURRENTS [2]

Before discussing the fundamentals of the measurement of the apparent charge, some remarks concerning the PD currents \( i(t) \) will be helpful, as much of the research work has been still devoted to these currents, which are difficult to measure with high accuracy. The difficulties arise for several reasons.

If \( V \) is an A.C. voltage, the main contribution of the currents flowing within the branches \( C_k \) and \( C_t \) of Figure 2.4 are displacement currents \( C(dV/dt) \), and both are nearly in phase. If no stray capacitance is in parallel to \( C_k \) were present, \( i(t) \) would be the same in both branches with opposite polarity. For accurate measurements, a shunt resistor with matched coaxial cable may be introduced in the circuit as shown in figure-2.4.

![Figure-2.4 Measurement of PD current i(t) – low sensitivity circuit](image)

The voltage across the CRO input (or transient recorder) is given by,

\[
V_m(t) = \frac{(i_k + i_t)Z_0R}{(R + Z_0)}
\]

\[\text{...(2.10)}\]
The test object having small capacitance then the voltages referring to the PD currents \( i(t) \) will be clearly distinguished from the displacement currents \( i_d(t) \).

Improvements are possible by inserting an amplifier (e.g. active voltage probe) of very high bandwidth at the input end of the signal cable. In this way, the signal cable is electrically disconnected from \( R \). High values of \( R \) will introduce measuring errors, which are explained with Figure-2.5. A capacitance \( C \) of some 10 pF, which accounts for the lead between \( C_t \) and earth as well as for the input capacitance of the amplifier or other stray capacitances, will shunt the resistance \( R \) and thus bypass or delay the very high-frequency components of the current \( i(t) \). Thus, if \( i(t) \) is a very short current pulse, its shape and crest value are heavily distorted, as \( C \) will act as an integrator. Furthermore, with \( R \) within the discharge circuit, the current pulse will be lengthened, as the charge transfer even with \( C=0 \) will be delayed by a time constant \( RC_t C_k/(C_t + C_k) \). Both effects are influencing the shape of the original current pulse, and thus the measurement of \( i(t) \) is a complicated task and can be accomplished in future work.

![Figure-2.5 Measurement of PD current – high sensitivity circuit](image)

All measured data on current shapes (which is published in many papers) are suffering from this effect. However, the results can be summarized by the following statements. Partial discharge currents originated in voids within solids or liquids are
very short current pulses of less than a few nanoseconds duration. This can be understood, as the gas discharge process within a very limited space is developed in a very short time and is terminated by the limited space for movement of the charge carriers. Discharges within a homogeneous dielectric material, i.e. a gas, produce PD currents with a very short rise time (≤5 ns) and a longer tail. Whereas the fast current rise is produced by the fast avalanche processes, the decay of the current can be attributed to the drift velocity of attached electrons and positive ions within the dielectric.

Discharge pulses in atmospheric air provide in general current pulses of less than about 100 nsec duration. Longer current pulses have only been measured for partial discharges in fluids or solid materials without pronounced voids, if a number of consecutive discharges take place within a short time. In most of these cases, the total duration of \( i(t) \) is less than about 1 µsec, with only some exceptions e.g. the usual bursts of discharges in insulating fluids.

All these statements refer to test circuits with very low inductance and proper damping effects within the loop \( C_k - C_t \). However, The current \( i(t) \) may oscillate and oscillations are readily excited by the sudden voltage drop across \( C_t \). Test objects with inherent inductivity or internal resonant circuits, e.g. transformer or reactor/generator windings, will always cause oscillatory PD current pulses. Such distortions of the PD currents, however, do not change the transferred charge magnitudes, as no discharge resistor is in parallel to \( C_k \) or \( C_t \). If the displacement currents \( i_d(t) \) or \( i_k(t) \) are suppressed, the distorted PD currents can also be filtered, integrated and displayed.
2.4 **Various PD Quantities**\textsuperscript{[2, 3]}

Partial discharge in any test object under given condition may be characterized by different measurable quantities like charge, repetition rate or integrated quantities etc.

**Apparent Charge (q):**

The apparent charge $q$ of a partial discharge is that charge which if injected instantaneously between the terminals of the test object, would momentarily change the voltage between its terminals by the same amount as the partial discharge itself and is expressed in pico coulombs. Final note is made with reference to the definition of the apparent charge $q$ (as given in the new IEC Standard 60270) is not equal to the amount of charge locally involved at the site of the discharge and which cannot be measured directly.

**Repetition Rate (n):**

It is the average number of partial discharge pulses per second measured over a selected time. In practice, only pulses above a specified magnitude or within a specified range of magnitudes may be considered.

**Specified PD Magnitude:**

It is the value the PD quantity stated in standards for the given test object at a specified voltage.

**Partial Discharge Inception Voltage ($V_i$):**

It is the lowest voltage at which PDs are observed in test arrangement,(in practice, lowest value at which PD' magnitude becomes equal to or exceeds a specified low value) when the voltage applied, to the object is gradually increased from a lower value at which no such discharges are observed,'
Partial Discharge Extinction Voltage ($V_e$):

It is the lowest voltage at which no PDs are observed in the test arrangement, (in practice, reduced below a specified value) when the voltage applied to the object is gradually decreased from a higher value at which such discharges are observed.

Partial Discharge Test Voltage:

PD test voltage is a specified voltage, applied in a specified test procedure, during which the test object should not exhibit partial discharges exceeding a specified magnitude.

The Average Discharge Current ($I$):

It is the sum of the absolute values of the apparent charges during a certain time interval divided by this time interval.

$$I = \frac{1}{T_{ref}} (|q_1| + |q_2| + ........ + |q_i|)$$  \hspace{1cm} ...(2.12)

The Quadratic Rate D:

It is the sum of the squares of the apparent charges during a certain time interval divided by this time interval.

$$D = I/T_{ref} (q_1^2 + q_2^2 + ... + q_i^2)$$ \hspace{1cm} ...(2.13)

The Discharge Power $p$:

It is the average power fed into the terminals of the test object due to partial discharges.

$$D = I/T_{ref} (q_1 u_1 + q_2 u_2 + ... + q_i u_i)$$ \hspace{1cm} ...(2.14)
Where \( u_1, u_2, \ldots, u_n \) are instantaneous values of the test voltage at the instants of occurrence \( t_i \) of the individual apparent charge magnitudes \( q_i \).

Additional quantities related to PD pulses, although already mentioned in earlier standards, will be used extensively in the future and thus their definitions are given below with brief comments only:

(a) The phase angle \( \Phi_i \) and time \( t_i \) is the occurrence of a PD pulse is

\[
\phi_i = 360 \left( \frac{t_i}{T} \right) \quad \text{...(2.15)}
\]

Where \( t_i \) is the time measured between the preceding positive going transition of the test voltage through zero and the PD pulse. Here \( T \) is the period of the test voltage.
2.5 Various PD Measurement Methods\textsuperscript{[2,3]}

The detection and measurement of discharges is based on the exchange of energy transform during the discharge. These exchanges include:

- Electrical pulse currents (with some exceptions, i.e. some types of glow discharges)
- Dielectric losses
- Electromagnetic radiation (light)
- Sound (noise)
- Increased gas pressure
- Chemical reactions

Therefore, discharge detection and measuring techniques may be based on the observation of any of the above phenomena.

Non-electrical methods of partial discharge detection include acoustical, optical and chemical methods and also the subsequent observation of the effects of any discharges on the test object. In general, these methods are not suitable for quantitative measurement of partial discharge quantities as defined in the standard by electrical measurement methods, but they are essentially used to detect and/or to locate the discharges.

Acoustic Detection:

Aural observations made in a room with low noise level may be used as a means of detecting partial discharges.
Visual or Optical Detection:

Visual observations can be carried out in a darkened room, after the eyes have become adapted to the dark and, if necessary, with the aid of binoculars of large aperture.

Chemical Detection:

The presence of partial discharges in oil or gas insulated apparatus may be detected in some cases by the analysis of the decomposition products dissolved in the oil or in the gas. These products accumulate during prolonged operation, so chemical analysis may be applicable to estimate the degradation, which has been caused by partial discharges.

The oldest and simplest method relies on listening to the acoustic noise from the discharge, the ‘hissing test’. This scheme has lower sensitivity and difficulties arise in distinguishing between discharges and extraneous noise sources, particularly when tests are carried out on factory premises. The use of optical techniques is limited to discharges within transparent media and thus not applicable in most of the cases. Latest acoustical detection methods utilize ultrasonic transducers, which can be used to localize the discharges.

The most frequently used and successful detection methods are the electrical ones where new IEC Standard is also related. These methods are aimed to separate the impulse currents linked with partial discharges from any other phenomena. The adequate applications of PD detectors are well defined and presume a fundamental knowledge of the electrical phenomena within the test samples and the test circuits. Electrical PD detection methods are based on the appearance of a ‘PD pulse’ at the terminals of a test object, which may be either a simple dielectric test specimen for fundamental investigations or even a large HV apparatus which has to undergo a PD test.
2.6 PD MEASURING SYSTEM WITHIN THE PD TEST CIRCUIT

In above sections the evolution of the PD current pulses and measurement procedures of these pulses have been broadly discussed. To quantify the individual apparent charge magnitudes \( q_i \) for the repeatedly occurring PD pulses; (which may have quite specific statistical distributions) a measuring system must be integrated into the test circuit. Already at this point, it shall be mentioned that under practical environment conditions, quite different kinds of disturbances (background noise) are present, which will be summarized in later section.

Most PD measuring systems applied are integrated into the test circuit in accordance with schemes shown in Figure-2.6(a) and Figure-2.6(b), which are taken from the new IEC Standard. Within these ‘straight detection circuits’, the coupling device ‘CD’ with its input impedance ‘\( Z_{mi} \)’ forms the input end of the measuring system.

As indicated in Figure-2.6(a), this device may also be placed at the high-voltage terminal side, provided if the test object has one terminal earthed. Optical links are then used to connect the CD with an instrument instead of a connecting cable ‘CC’. Some essential requirements and explanations with reference to these figures as indicated by the standard are cited here:

The coupling capacitor \( C_k \) shall be of low inductance design and should exhibit a sufficiently low level of partial discharges at the specified test voltage to allow the measurement of the specified partial discharge magnitude. A higher level of partial discharges can be tolerated if the measuring system is capable of separating the discharges from the test object and the coupling capacitor and measuring them separately.

The high voltage supply shall have sufficiently low level of background noise to allow the specified partial discharge magnitude to be measured at the specified test
voltage. Impedance of a filter may be introduced at high voltage to reduce background noise from the power supply.

The main difference between these two types of PD detection circuits is related to the way the measuring system is inserted into the circuit. Figure-2.6(a) shows the CD is at ground potential and in series to the coupling capacitor $C_k$ as it is usually done in praxis. Figure-2.6(b) shows CD is in series with the test object $C_a$.

Figure-2.6 Basic Partial Discharge Detection Test Circuit – Straight Detection

Figure-2.6 refers following notations:

- $U_\sim$ = High voltage supply
- $Z_{mi}$ = Input impedance of measuring system
CC = connecting cable
OL = optical link
C_a = test object
C_k = coupling capacitor
CD = coupling device
MI = measuring instrument

Here, the stray capacitances of all elements of the high-voltage side to ground potential will increase the value of C_k providing a somewhat higher sensitivity for this circuit according to equation-2.7. The disadvantage is the possibility of damage to the PD measuring system, if the test object fails. The transfer impedance Z(f) is the ratio of the output voltage amplitude to a constant input current amplitude, as a function of frequency f, when the input is sinusoidal. This definition is due to the fact that any kind of output signal of a measuring instrument (MI) as used for monitoring PD signals is controlled by a voltage, whereas the input at the CD is a current.

The lower and upper limit frequencies f_1 and f_2 are the frequencies at which the transfer impedance Z(f) has fallen by 6 dB from the peak pass band value. Mid-band frequency f_m and bandwidth Δf for all kinds of measuring systems, the mid-band frequency is defined by,

\[ f_m = \frac{(f_1 + f_2)}{2} \]  
\[ \text{...(2.16)} \]

and the bandwidth by,

\[ Δf = f_2 - f_1 \]  
\[ \text{...(2.17)} \]

The superposition error is caused by the overlapping of transient output pulse responses when the time interval between input current pulses is less than the duration
of a single output response pulse. Superposition errors may be additive or subtractive depending on the pulse repetition rate ‘n’ of the input pulses. In practical circuits, both types will occur due to the random nature of the pulse repetition rate. This rate ‘n’ is defined as the ratio of total number of PD pulses recorded in a selected time interval to the duration of the time interval.

The pulse resolution time $T_r$ is the shortest time interval between two consecutive input pulses of very short duration, of same shape, polarity and charge magnitude for which the peak value of the resulting response will change by not more than 10 per cent of that for a single pulse. The pulse resolution time is in general inversely proportional to the bandwidth $\Delta f$ of the measuring system. It is an indication of the measuring system’s ability to resolve successive PD events.

Figure-2.7 shows correct relationship between amplitude and frequency to minimize integration errors for a wide-band system. The integration error is the error in apparent charge measurement, which occurs when the upper frequency limit of the PD current pulse amplitude spectrum is lower than (i) the upper cut-off frequency of a wideband measuring system or (ii) the mid-band frequency of a narrow-band measuring system.

![Figure-2.7 Correct Relationship Between Amplitude and Frequency to Minimize Integration Errors for a Wide-band System](image)
As shown in figure-2.7,

A is a band-pass of the measuring system

B is an amplitude frequency spectrum of the PD pulse

C is an amplitude frequency spectrum of calibration pulse

\( f_1 \) is lower limit frequency

\( f_2 \) is upper limit frequency

PD measuring systems quantifying apparent charge magnitudes are band-pass systems, which predominantly are able to suppress the high power frequency displacement currents including higher harmonics.

The lower frequency limit of the band-pass \( f_1 \) and the kind of ‘roll-off’ of the bandpass control this ability. Adequate integration can thus only be made if the ‘pass-band’ of the filter is still within the constant part of the amplitude frequency spectrum of the PD pulse to be measured. Next topic discusses basic types of PD instruments to measure PD.

**Measuring System For Apparent Charge**

The following type of measuring system comprises subsystems like, coupling device (CD), transmission system or connecting cable (CC), and a measuring instrument (MI) as seen in figure-2.6. In general the transmission system, necessary to transmit the output signal of the CD to the input of the MI, does not contribute to the measuring system characteristics as both ends are matched to the characteristics of both elements. The CC will thus not be considered further.
The input impedance $Z_{mi}$ of the CD or measuring system respectively will have some influence on the waveshape of the PD current pulse $i(t)$, which is already mentioned in the figure-2.5 description. The high input impedance will delay the charge transfer between $C_a$ and $C_k$ to such an extent that the upper limit frequency of the amplitude frequency spectrum would drop to unacceptable low values. Often, values of $Z_{mi}$ are in the range of 100 $\Omega$. In common with the first two measuring systems for apparent charge is a newly defined ‘pulse train response’ of the instruments to quantify the ‘largest repeatedly occurring PD magnitude’, which is taken as a measure of the ‘specified partial discharge magnitude’, permitted in test objects during acceptance tests under specified test conditions.

Sequences of partial discharges follow in general unknown statistical distributions and it would be useless to quantify only one or very few discharges of large magnitude within a large array of much smaller events as a specified PD magnitude. For further information on quantitative requirements about this pulse train response, which was not specified up to now and thus may not be found within in earlier instruments.

**WIDE BAND PD INSTRUMENTS**

Up to 1999, no specifications or recommendations concerning to permitted response parameters have been available. Now, the following parameters are recommended. In combination with the CD, wide-band PD measuring systems, which are characterized by a transfer impedance $Z(f)$ having fixed values of the lower and upper limit frequencies $f_1$ and $f_2$, and adequate attenuation below $f_1$ and above $f_2$, shall be designed to have the following values for $f_1$, $f_2$ and $\Delta f$:

$$30 \text{ kHz} \leq f_1 \leq 100 \text{ kHz}$$

$$f_2 \leq 500 \text{ kHz}$$

$$100 \text{ kHz} \leq \Delta f \leq 400 \text{ kHz}$$
The response of these instruments to a (non-oscillating) PD current pulse is in general a well-damped oscillation as shown below. Both the apparent charge $q$ and with some reservation the polarity of the PD current pulse can be determined from this response. The pulse resolution time $T_r$ is small and is typically 5–20 µs.

Figure-2.8 shows the typical principle of such a system and Figure-2.8(a) shows simplified equivalent circuit for the CD and amplifier whereas Figure-2.8(b) shows typical time-dependent quantities within (a) ($T =$ period of power frequency; $\tau =$ pulse resolution time $T_r$)

![Diagram of principle of 'Wide-band' PD Measuring System](image)
The coupling devices CD (Figure-2.6) are passive high-pass systems but behave more often as a parallel R-L-C resonance circuit (Figure-2.8(a)) whose quality factor is relatively low. Such coupling impedance provides two important qualities.

At first, a simple calculation, which is the ratio of output voltage $V_0$ to input current $I_i$ in dependency of frequency (= transfer impedance $Z(f)$) would readily demonstrate an adequate suppression of low and high frequency currents in the neighborhood of its resonance frequency. For a quality factor of $Q = 1$, this attenuation is already $-20\text{dB/decade}$ and could be greatly increased close to resonance frequency by increasing the values of $Q$. Secondly, this parallel circuit also performs an integration of the PD currents $i(t)$, as this circuit is already a simple band-pass filter and can be used as an integrating device.

Let us assume that the PD current pulse $i(t)$ will not be influenced by the test circuit and would be of an extremely short duration pulse, simulated by a Dirac function comprising the apparent charge $q$. Then the calculation of the output voltage $V_0(t)$ according to Figure-2.8(a) results in:

$$V_0(t) = \frac{q}{C}e^{-\alpha t} \left[ \cos \beta t - \frac{\alpha}{\beta} \sin \beta t \right] \quad \ldots(2.18)$$

Where,

$$\alpha = \frac{1}{2RC} \quad \beta = \sqrt{\frac{1}{LC} - \alpha^2} = \omega_0 \sqrt{1 - \alpha^2LC} \quad \ldots(2.19)$$

This equation displays a damped oscillatory output voltage, whose amplitudes are proportional to $q$. The integration of $i(t)$ is thus performed instantaneously ($t=0$) by the capacitance $C$, but the oscillations, if not damped, would heavily increase the ‘pulse resolution time $T_r$’ of the measuring circuit and cause ‘superposition errors’ for too short time intervals between consecutive PD events.
With a quality factor of \( Q = 1 \), i.e. \( R = \sqrt{\frac{L}{C}} \), a very efficient damping can be achieved, since \( \alpha = \frac{\omega_0}{2} = \pi f_0 \) for a resonance frequency \( f_0 \) of typically 100 kHz, and an approximate resolution time of \( T_r \cong t = \frac{3}{\alpha} \), this time becomes about 10 \( \mu \)sec.

For higher \( Q \) values, \( T_r \) will be longer, but also the filter efficiency will increase and therefore a compromise is necessary. The resonance frequency \( f_0 \) is also influenced by the main test circuit elements \( C_k \) and \( C_a \), as their series connection contributes to \( C \). Therefore the ‘RLC input units’ must be changed according to specimen capacitance to achieve a bandwidth or resonance frequency \( f_0 \) within certain limits. These limits are postulated by the bandwidth \( \Delta f \) of the additional band-pass amplifier connected to this resonant circuit to increase the sensitivity and thus to provide again an integration.

These amplifiers are typically designed for lower and upper limit frequencies of some 10 kHz and some 100 kHz respectively, and sometimes the lower limit frequency range may also be switched from some 10 kHz up to about 150 kHz to further suppress power frequencies. In general the fixed limit frequencies are thus within a frequency band and are not used by radio stations and higher than the harmonics of the power supply voltages.

The band-pass amplifier has in general variable amplification to feed the ‘CRO’ (reading device) following the amplifier with adequate magnitudes during calibration and measurement. Figure-2.8(b) shows the time-dependent quantities (input a.c. current with superimposed PD signals, voltages before and after amplification).

Figure-2.9 shows the amplified discharge pulses are in general displayed by an (analogue or digital) oscilloscope superimposed on a power frequency elliptic time base. The magnitude of the individual PD pulses is then quantified by comparing the pulse crest values with those produced during a calibration procedure. With this type of reading by individual persons it is not possible to quantify the standardized ‘pulse
train response’ which quantifies the ‘largest repeatedly occurring PD magnitude’. Correct readings are, however, possible by applying additional analogue peak detection circuits or digital peak detection software prepared to follow the specified pulse train response. The pattern on the CRO display can often be used to recognize the origin of the PD sources. (Instead of a simple CRO display digital acquisition of PD quantities and up-to-date methods for evaluation are used now).

Figure-2.9 Elliptical Display

(a) Point plane (‘Trichel pulses’)

(b) Void discharges at inception

(c) Void discharges at twice inception voltage
A typical pattern of Trichel pulses can be seen in figure-2.9(a). Figure-2.9(b), is typical for the case for which the pulse resolution time of the measuring system including the test circuit, which is too large to distinguish between individual PD pulses.

It was clearly shown that even the response of such ‘wide-band PD instruments’ provide no more information about the original shape of the input PD current pulse as indicated in figure-2.8(b) and confirmed by the pattern of the Trichel pulses in figure-2.9(a). Figure-2.10 further confirms this statement. Figure-2.10 shows two recorded responses for two consecutive calibration pulses (‘double pulse’) are shown within a time scale of microseconds.
A comparison of both recorded responses shows their differences with respect to a (positive) short and lengthened input pulse, which has some significant influence on the peak value of the undershoot after the first excursion of the response which indicates the polarity of the input signal. Polarity detection by digital PD acquisition systems may thus be difficult.

**NARROW – BAND PD INSTRUMENTS**

It is well known that radio transmission or radiotelephony may be heavily disturbed by high-frequency interference voltages within the supply mains to which receivers
are connected or by disturbing electromagnetic fields picked up by the aerials. It was also early recognized that corona discharges at HV transmission lines are the source of such disturbances. The measurement of ‘radio noise’ in the vicinity of such transmission lines is thus an old and well-known technique which several decades ago triggered the application of this measurement technique to detect insulation failures, i.e. partial discharges, within HV apparatus of any kind.

The methods for the measurement of radio noise or radio disturbance have been subjected to many modifications during the past decades. Apart from many older national or international recommendations, the latest ‘specifications for radio disturbance and immunity measuring apparatus and methods’ within a frequency range of 10 kHz to 1000 MHz are now described in the CISPR Publication. As defined in this specification, the expression ‘radio disturbance voltage (RDV)’, earlier termed as ‘radio noise’, ‘radio influence’ or ‘radio interference’ voltages, is now used to characterize the measured disturbance quantity.

Narrow-band PD instruments, which are now also specified within the new IEC Standard for the measurement of the apparent charge, are very similar to those RDV meters, which are applied for RDV measurements in the frequency range 100 kHz to 30MHz.

The PD instruments are characterized by a small bandwidth $\Delta f$ and a mid-band frequency $f_m$, which can be varied over a wider frequency range, where the amplitude frequency spectrum of the PD current pulses is in general approximately constant. The recommended values for $\Delta f$ and $f_m$ for PD instruments are

\[
9 \text{ kHz} \leq \Delta f \leq 30 \text{ kHz}
\]

\[
50 \text{ kHz} \leq f_m \leq 1 \text{ MHz}
\]
It is further recommended that the transfer impedance $Z(f)$ at frequencies of $f_m \pm \Delta f$ should already be 20 dB below the peak pass-band value. Commercial instruments of this type may be designed for a larger range of mid-band frequencies; therefore, the standard provides the following note for the user. ‘During actual apparent charge measurements, mid-band frequencies $f_m > 1$MHz should only be applied if the readings for such higher values do not differ from those as monitored for the recommended values of $f_m$’.

This statement denotes that only the constant part of the PD current amplitude\ frequency spectrum is an image of the apparent charge. As shown below in more detail, the response of these instruments to a PD current pulse is a transient oscillation with the positive and negative peak values of its envelope proportional to the apparent charge, independent of the polarity of this charge.

Due to the small values of $\Delta f$, the pulse resolution time $T_r$ will be large, typically above 80 $\mu$s. The application of such instruments often causes some confusion for the user. A brief description of their basic working principle and their use in PD measurements will help make things clear. Figure-2.11 displays the relevant situation and results.

In general, such instruments are used together with coupling devices providing high-pass characteristics within the frequency range of the instrument. Power frequency input currents including harmonics are therefore suppressed and assumed that only the PD current pulses converted to PD voltage pulses are at the input of the amplifying instrument, which resembles closely a selective voltmeter of high sensitivity (or a super heterodyne-type receiver) which can be tuned within the frequency range of interest.

Such a narrow-band instrument is again a quasi integration device for input voltage pulses. To demonstrate this behavior, it is assumed that an input voltage $V_1 = V_0 e^{-ct}$
\( v(T) \), i.e. an exponentially decaying input pulse which starts suddenly with amplitude \( V_0 \) (see Figure-2.11(b)). The integral of this pulse, \( \int_{0}^{\infty} v_1(t) \, dt \), is \( V_0 T \) and is thus a quantity proportional to the apparent charge \( q \) of a PD current pulse. The complex frequency spectrum of this impulse is then given by applying the Fourier integral

\[
V_1(j\omega) = \int_{0}^{\infty} v_1(t) \exp(-j\omega t) \, dt = \frac{V_0 T}{1 + j\omega T} = \frac{S_0 T}{1 + j\omega T} \quad \text{...(2.20)}
\]

and the amplitude frequency spectrum \( |V_1(i\omega)| \) by

\[
|V_1(j\omega)| = \frac{V_0 T}{\sqrt{1 + (\omega T)^2}} = \frac{S_0}{\sqrt{1 + (\omega T)^2}} \quad \text{...(2.21)}
\]

where \( S_0 \) is proportional to \( q \). From the amplitude frequency spectrum, sketched in Figure-2.11(c), it is obvious that the amplitudes decay already to -3 dB or more than about 30 per cent for the angular frequency of \( \omega_c > (1/T) \). This critical frequency \( f_c \) is for \( T = 0.1 \) µsec only 1.6 MHz, a value which can be assumed for many PD impulses.
Figure-2.11 Narrow-band Amplifiers Responses (Part-1)
As the indication of a narrow-band instrument, if tuned to $f_m$, will be proportional to the relevant amplitude of this spectrum at $f_m$, then the recommendations of the new standard can well be understood. If the input PD current pulse were distorted by
oscillations, the amplitude frequency spectrum would also be distorted by maxima and minima, which can then be recorded by tuning \( f_m \).

If the narrow-band instrument is tuned to the constant part of the spectrum which is proportional to \( q \), and assumed a Dirac pulse or delta function of magnitude \( V_0T = S_0 \) to calculate its output voltage \( V_2(t) \).

As the spectrum of a Dirac pulse is constant for all frequencies, the response \( V_2(t) \) is then proportional to \( S_0 \) at any frequency \( f_m \). The impulse response of the instrument is then of course dependent upon the exact (output/input voltage) transfer function \( G(j\omega) \) of the system. However, the actual band-pass characteristic by an idealized one as shown in Figure-2.11(d), with a mid-band angular frequency \( \omega_m \), an angular bandwidth \( \Delta\omega \) and the constant amplitude or ‘scale factor’ \( G_0 \) within \( \omega_m \pm (\Delta\omega/2) \).

For such ideal band-pass systems and especially narrow-band amplifiers the phase shift \( \Phi(\omega) \) may well be assumed to be linear with frequency as indicated, at least within the band-pass response. With this approximation no phase distortion is assumed, and \( t_0 \) (figure-2.11(d)) is equal to the delay time of the system. The impulse response with \( S_0 \) as input pulse appearing at \( t = 0 \) can then be evaluated from

\[
v_2(t) = \frac{1}{\pi} \int_{\omega_m-\Delta\omega/2}^{\omega_m+\Delta\omega/2} S_0 G_0 \cos[\omega(t-t_0)] d\omega \quad \text{...(2.22)}
\]

This integral can easily be solved; the result is

\[
v_2(t) = \frac{S_0 G_0 \Delta\omega}{\pi} \left[ \frac{\Delta\omega}{2} (t-t_0) \right] \cos \left( \frac{\omega_m}{2} (t-t_0) \right) \quad \text{...(2.23)}
\]

Where \( \text{si}(x) = \text{Sin} (x) / x \)

Equation-2.15 shows an oscillating response whose main frequency is given by \( f_m = \omega_m / 2\pi \), the amplitudes are essentially given by the \( \text{si}(x) \) function, which is the
envelope of the oscillations. A calculated example for such a response is shown in figure-2.11(e). The maximum value will be reached for $t = t_0$ and is clearly given by

$$V_{2\text{max}} = \frac{S_0 G_0 \Delta \omega}{\pi} = 2S_0 G_0 \Delta f$$

…(2.24)

where $\Delta f$ is the idealized bandwidth of the system.

Here, the two main disadvantages of narrow-band receivers can easily be seen: first, for $\Delta \omega << \omega_m$ the positive and negative peak values of the response are equal and therefore the polarity of the input pulse cannot be detected. The second disadvantage is related to the long duration of the response. Although more realistic narrow band systems will effectively avoid the response amplitudes outside of the first zero values of the $(\sin x)/x$ function, the full length $\tau$ of the response, with $\tau$ as defined by figure-2.11(e), becomes

$$\tau = \frac{2}{(\Delta f)} = \frac{4\pi}{\Delta \omega}$$

…(2.25)

In above equation $\tau$ is quite large for small values of $\Delta f$ and the actual definition of the ‘pulse resolution time $T_r$ ’ as defined before. This quantity is about 10% smaller than $\tau$, but still much larger than for wide-band PD detectors.

Simple narrow-band detectors use only RLC resonant circuits with high quality factors $Q$, the resonance frequency of which cannot be tuned. Although then their responses are still quite similar to the calculated one (equation-2.23), figure-2.12 shown such a response for a ‘double pulse’ taken from a commercial PD instrument.
RADIO DISTURBANCE (INTERFERENCE) METERS FOR THE DETECTION OF PD

As instruments such as those specified by the International Special Committee on Radio Disturbance or similar organizations are still in common uses for PD detection. The possible application of an ‘RDV’ or ‘RIV’ meter is still mentioned within the new standard.

New types of instruments related to the CISPR Standard are often able to measure ‘radio disturbance voltages, currents and fields’ within a very large frequency range, based on different treatment of the input quantity. Within the PD standard, however, the expression ‘Radio Disturbance Meter’ is only applied for a specific radio disturbance (interference) measuring apparatus, which is specified for a frequency band of 150 kHz to 30MHz (band B) and which fulfils the requirements for a so-called ‘quasi-peak measuring receivers’.

Figure-2.13 shows diagram of such a simple RIV meter, which is compared with the principle of a narrow-band PD instrument as, described and discussed before. The main difference is only the ‘quasi-peak’ or ‘psopho- metric weighting circuit’ that simulates the physiological noise response of the human ear. As already mentioned within the introduction of this section, forthcoming PD instruments will be equipped
with a similar, but different circuit with a ‘pulse train response’ quantifying the ‘largest repeatedly occurring PD magnitudes’.

Within the figure-2.13, the simplified coupling device as indicated by a resistance shunted by the inductance L forms transfer impedance $Z_m$ with a high-pass characteristic which for RDV meters are standardized values. Based on the derivations as already made for the calculation equation-2.24 can easily quantify the differences of both types of meter.

Figure-2.13 Block Diagram of a Quasi-peak RIV Meter Including Weighting Circuit Compared with PD Narrow-band PD Detector
The quasi-peak RDV meters are designed with a very accurately defined overall passband characteristic fixed at $\Delta f = 9$ kHz. They are calibrated in such a way that the response to Dirac type of equidistant input pulses providing each a volt–time area of 0.316 $\mu$Vs at a pulse repetition frequency (N) of 100Hz. This is equal to an unmodulated sine-wave signal at the tuned frequency having an e.m.f. of 2mV r.m.s. as taken from a signal generator driving the same output impedance as the pulse generator and the input impedance of the RIV meter.

By this procedure the impulse voltages as well as the sine-wave signal are halved. As for this repetition frequency of 100Hz the calibration point shall be only 50 per cent of $V_{2\text{max}}$ in eqn. (2.16), the relevant reading of the RDV meter will be

$$E_{RDV} = \frac{1}{2\sqrt{2}} 2S_0G_0\Delta f = \frac{S_0G_0\Delta f}{\sqrt{2}} \quad \text{...(2.26)}$$

As $G_0 = 1$ for a proper calibration and $\Delta f = 9$kHz, $S_0 = 158 \mu$Vs, the indicated quantity is $S_0\Delta f/\sqrt{2}= 1$mV or 60dB ($\mu$V), as the usual reference quantity is 1 $\mu$V. RDV meters are thus often called ‘microvolt meters’.

This response is now weighted by the ‘quasi-peak measuring circuit’ with a specified electrical charging time constant $\tau_1 = 1$ms, an electrical discharging time constant $\tau_2 = 160$ ms and by an output voltmeter, which, for conventional instruments, is of moving coil type, critically damped and having a mechanical time constant $\tau_3 = 160$ms.
This procedure makes the reading of the output voltmeter dependent on the pulse repetition frequency $N$. This non-linear function $f(N)$ is shown in figure-2.14 and is only accurate if the input pulses are equidistant and of equal amplitudes. It can be seen that for $N > 1000$ the function $f(N)$ would saturate to a value of 2, for which, however, superposition errors occur.

With this function $f(N)$ we can now finalize the reading of an RIV meter by taking the transfer impedance $Z_m$ of CD in eqn (2.18) into account, which converts input PD currents into input voltages $v_1(t)$. For RDV meters, this transfer impedance, the real value of which $|Z_m|$ is constant for the frequency range under consideration, the quantity $S_0$ in eqn. (2.18) may then be written as,

$$S_0 = \int v_1(t)dt = |Z_m|\int i_1(t)dt = |Z_m|q$$ \hspace{1cm} (2.27)

Where $q$ is the measured charge quantity for an impulse current $i_1(t)$. Here, eq-2.18 can be rewritten as $E_{RDV} = \frac{G_0}{\sqrt{2}}q\Delta f|Z_m|f(N)$ and conversion factors between the
measured charge $q$ and the indicated voltage by an RDV meter can be calculated. For $N = 100$ equidistant pulses of equal magnitude $f(N) = 1$, $\Delta f = 9$ kHz, correct calibration $G_0 = 1$ and a reading of 1mV ($E_{RDV}$) or 60 dB, charge magnitudes of 1 nC for $|Z_m| = 150$ (or 60) $\Omega$ can be calculated. These relationships have also been confirmed experimentally. Instead of eqn (2.19) the new standard displays.

$$U_{RDV} = \left( q \Delta f Z_m f(N) \right) / k_i$$

...(2.28)

where

$N$ = pulse repetition frequency,

$f(N)$ = the non-linear function of $N$ (see figure-2.14),

$\Delta f$ = instrument bandwidth (at 6 dB),

$Z_m$ = value of a purely resistive measuring input impedance of the instrument,

$k_i$ = the scale factor for the instrument (= $q / U_{RDV}$)

As the weighting of the PD pulses is different for narrow-band PD instruments and quasi-peak RDV meters, there is no generally applicable conversion factor between readings of the two instruments. The application of RDV meters is thus not forbidden; but if applied the records of the tests should include the readings obtained in microvolt and the determined apparent charge in pico coulombs together with relevant information concerning their determination.

**ULTRA-WIDE-BAND INSTRUMENTS FOR PD DETECTION**

The measurement of PD current pulses belongs to this kind of PD detection as well as any similar electrical method to quantify the intensity of PD activities within a test object. Such methods need coupling devices with high-pass characteristics which shall have a pass band up to frequencies of some 100MHz or even higher.
Records of the PD events are then taken by oscilloscopes, transient digitizers or frequency selective voltmeters especially spectrum analyzers. For the location of isolated voids with partial discharges in cables a bandwidth of about some 10MHz only is useful, whereas tests on GIS (gas-insulated substations or apparatus) measuring systems with ‘very high’ or even ‘ultra-high’ frequencies (VHF or UHF methods for PD detection) can be applied.

The development of any partial discharge in sulphur hexafluoride is of extremely short duration providing significant amplitude frequency spectra up to the GHz region. More information concerning this technique can be found in the literature.

As none of these methods provides integration capabilities, they cannot quantify apparent charge magnitudes, but may well be used as a diagnostic tool.
2.7 CALIBRATION OF PD DETECTORS IN A COMPLETE TEST CIRCUIT [3]

The reasons why any PD instrument provides continuously variable sensitivity must be calibrated in the complete test circuit, which has been explained before. Even the definition of the ‘apparent charge q’ is based on a routine calibration procedure, which shall be made with each new test object. Calibration procedures for PD detection are thus firmly defined within the standard.

A calibration of measuring systems intended for the measurement of the fundamental quantity q is made by injecting short duration repetitive current pulses of well-known charge magnitudes $q_0$ across the test object, subject to any test circuit as shown in Figure-2.15. These current pulses are generally derived from a calibrator which comprises a generator producing step voltage pulses (see ‘G’) of amplitude $V_0$ in series with a precision capacitor $C_0$. If the voltages $V_0$ also remain stable and are exactly known, repetitive calibration pulses with charge magnitudes of $q_0=V_0C_0$ are injected. A short rise time of 60 ns is now specified for the voltage generator to produce current pulses with amplitude-frequency spectra which fit into the requirements set by the bandwidth of the instruments and avoids integration errors if possible.

![Figure-2.15 The Usual Circuit for the Calibration of a PD Measuring Instrument MI within the Complete Test Circuit.](Image)
Whereas further details for the calibration procedures are not discussed here, the new philosophy in reducing measuring errors during PD tests will be presented. It has been known for some time that measuring uncertainties in PD measurements are large. Even today PD tests on identical test objects performed with different types of commercially available systems will provide different results after routine calibration performed with the same calibrator.

The main reasons for this uncertainty are the different transfer impedances (bandwidth) of the measuring systems, which up to 1999 have never been well defined and quantified. The new but not very stringent requirements related to this property will improve the situation; together with other difficulties related to disturbance levels, measures uncertainties of more than about 10 per cent (if exists). The most essential part of the new philosophy concerns the calibrators, for which – up to now – no requirements for their performance exists.

Tests on daily used commercial calibrators sometime display deviations of more than 10 per cent of their nominal values. Therefore routine type and performance tests on calibrators have been introduced with the new standard. At least the first of otherwise periodic performance tests should be traceable to national standards, this means they shall be performed by any accredited calibration laboratory. With the introduction of this requirement it can be assumed that the uncertainty of the calibrator charge magnitudes $q_0$ can be assessed to remain within $\pm 5$ per cent or 1 pC, whichever is greater, from its nominal values. Very recently executed inter-comparison tests on calibrators performed by accredited calibration laboratories showed that impulse charges could be measured with an uncertainty of about 3 per cent.
2.8 **Digital Instruments for PD Measurements** [2]

Between 1970 and 1980 the state of the art in computer technology and related techniques rendered the first application of digital acquisition and processing of partial discharge magnitudes. Since then this technology was applied in numerous investigations generally made with either instrumentation set up with available components or some commercial instruments equipped with digital techniques.

One task for the working group evaluating the new IEC Standard concerned with implementation of few key requirements for this technology. It is again not the aim of this section to go into details of digital PD instruments, as too many variations in designing such instruments exist.

In general, digital PD instruments are based on analogue measuring systems or instruments for the measurement of the apparent charge \( q \) followed by a digital acquisition and processing system. These digital parts of the system are then used to process analogue signals for further evaluation, to store relevant quantities and to display test results.

It is possible that in the near future a digital PD instrument may also be based on a high-pass coupling device and a digital acquisition system without the analogue signal processing front end. The availability of cheap but extremely fast flash A/D converters and digital signal processors (DSPs) performing signal integration is a prerequisite for such solutions.

The main objective of applying digital techniques to PD measurements is based on recording in real time and most of consecutive PD pulses are within a voltage cycle of the test voltage. These PD pulses are quantified by its apparent charge \( q_i \) (occurring at time instant \( t_i \)) and its instantaneous values of the test voltage \( u_i \) (occurring at this time instant \( t_i \)) or for alternating voltages, at phase angle of \( \Phi_i \)
As, however, the quality of hardware and software used may limit the accuracy and resolution of the measurement of these parameters, the new standard provides some recommendations and requirements which are relevant for capturing and registration of the discharge sequences. One of the main problems in capturing the output signals from the analogue front end correctly can be seen from Figures-2.12 and Figure-2.14 respectively, in which three output signals of two consecutive PD events are shown.

Although none of the signals is distorted by superposition errors, several peaks of each signal with different polarities are present. For the wideband signals, only the first peak value shall be captured and recorded including polarity, which is not easy to do. For the narrow-band response for which polarity determination is not necessary, only the largest peak is proportional to the apparent charge.

For both types of signals therefore only one peak value shall be quantified, recorded and stored within the pulse resolution time of the analogue measuring system. Additional errors can well be introduced by capturing wrong peak values, which add to the errors of the analogue front end.

Further study of PD instruments is related to post-processing of the recorded values. Firstly; the so-called ‘\(\varphi_i - q_i - n_i\)’ patterns, available from the recorded and stored data in which \(n_i\) is the number of identical or similar PD magnitudes recorded within short time (or phase) intervals and an adequate total recording duration can be used to identify and localize the origin of the PDs based on earlier experience and/or even to establish physical models for specific PD processes. If recorded raw data are too much obscured by disturbances, quite different numerical methods may also be applied for disturbance level reduction.

This chapter concludes with two records of results from PD tests made with digital PD instrument. Figure-2.16 and figure-2.17, individually, shows typical test results of
phase resolved PD measurement for a moving metal particle within a GIS and on-site PD measurements performed on HV cable (at a terminator).

Figure-2.16 The Pattern of a Phase-resolved PD Measurement for a Moving Metal Particle within a GIS.
Figure-2.17 An Example of a $\phi$ - $q$ - $n$ Diagram. On-site PD measurements performed on an HV cable, heavy partial discharges at a terminator.
2.9 **Source of Interference and Reduction of Disturbances** \[2, 3\]

One of the most difficult problems that must be coped with in making PD measurements is that of electrical interference (noise) which falls into following categories:

- Disturbances, which occur if test circuit is not energized. They may be caused by switching operations in other circuits, commuting machines, high voltage tests in the vicinity radio transmission etc.
- Disturbances which only occur when the test circuit is energized but which don’t occur in the test object, for e.g. PD in testing transformer, HV conductors, bushings, disturbances caused by sparking of imperfectly earthed objects in the vicinity or the loose connections in the area of high voltages.
- Disturbances which may also caused by higher harmonics of test voltage within the band-width of the measuring instruments. These disturbances usually increase with increasing the voltage.

These disturbances can seriously affect the sensitivity of the test circuit and must be controlled and suppressed to minimum and to use detectors equipped with an oscilloscope to give the maximum opportunity for distinguishing spurious signals from the discharges in the test sample.

The following table gives the complete account of different sources of disturbances and their control or remedy for suppression.

All preceding disturbances can be suppressed by using a balance detection method.
<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Example</th>
<th>Control or remedy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disturbance in the circuit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mains interference</td>
<td>Filter in feeding leads and/or in H.V. Line</td>
<td></td>
</tr>
<tr>
<td>H.V. Source</td>
<td>Discharge free H.V. transformer, filter in H.V. line</td>
<td></td>
</tr>
<tr>
<td>Coupling Capacitor</td>
<td>Coupling capacitor should be discharge free or two samples should be tested at a time</td>
<td></td>
</tr>
<tr>
<td>Terminals</td>
<td>Discharge in cable terminals, bushings etc.</td>
<td>Terminals, bushings etc should be discharge free.</td>
</tr>
</tbody>
</table>

* All preceding disturbance can be suppressed by using a balanced detector

<table>
<thead>
<tr>
<th>Pick-up</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Other H.V. tests in the vicinity</td>
<td>Screening, eliminating the cause</td>
<td></td>
</tr>
<tr>
<td>Electromagnetic waves</td>
<td>Radio signals</td>
<td>Screening, a detector below about 100KHz can be chosen</td>
</tr>
<tr>
<td>Induced discharger</td>
<td></td>
<td>Eliminating the cause, proper earthing, screening samples should be tested at a time</td>
</tr>
</tbody>
</table>

* Screening is effective in 3-preceding cases.

<table>
<thead>
<tr>
<th>Contact noise</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact noise in circuit</td>
<td>Making good connection and earthing also in variable components in the input circuit</td>
<td></td>
</tr>
<tr>
<td>Contact noise in sample</td>
<td>Contact between the foils and terminals in capacitor</td>
<td>Applying current impulses by short circulating.</td>
</tr>
<tr>
<td></td>
<td>Contact noise in bushing, tap changer or earthing of the core in the transformer</td>
<td>Checking contacts before mounting</td>
</tr>
<tr>
<td></td>
<td>Contacts between semi conducting layer and metallic sheath of cable</td>
<td>Choosing smaller time constants (equal to higher resolution) of input circuit</td>
</tr>
</tbody>
</table>
It is obvious that up to now numerous methods to reduce disturbances have been and still are a topic for research and development, which can only be mentioned and summarized here.

The most efficient method to reduce disturbances is screening and filtering, in general only possible for tests within a shielded laboratory where all electrical connections running into the room are equipped with filters. This method is expensive, but inevitable if sensitive measurements are required, i.e. if the PD magnitudes as specified for the test objects are small, e.g. for HV cables.

Straight PD-detection circuits as already shown in Figure-2.6 are very sensitive to disturbances: any discharge within the entire circuit, including HV source, which is not generated in the test specimen itself, will be detected by the coupling device CD. Therefore, such ‘external’ disturbances are not rejected. Independent of screening and filtering mentioned above, the testing transformer itself should be PD free as far as possible, as HV filters or inductors indicated in figure-2.6 are expensive. It is also difficult to avoid any partial discharges at the HV leads of the test circuit, if the test voltages are very high. A basic improvement of the straight detection circuit may therefore become necessary by applying a ‘balanced circuit’, which is similar to a Schering bridge.

Figure-2.18 shows the coupling capacitor $C_k$ and test specimen $C_t$ form the HV arm of the bridge, and the LV arms are basically analogous to a Schering bridge. As $C_k$ is not a standard capacitor but should be PD free, the dissipation factor $\tan \delta_k$ may also be higher than that of $C_t$, and therefore the capacitive branch of the LV arm may be switched to any of the two arms. The bridge can then be adjusted for balance for all frequencies at which $\tan \delta_k = \tan \delta_t$. This condition is best fulfilled if the same insulation media are used within both capacitors.
The use of a partial discharge-free sample for $C_k$ of the same type as used in $C_t$ is thus advantageous. If the frequency dependence of the dissipation factors is different in the two capacitors, a complete balance within a larger frequency range is not possible. Nevertheless, a fairly good balance can be reached and therefore most of the sinusoidal or transient voltages appearing at the input ends of $C_k$ and $C_t$ cancel out between the points 1 and 2. A discharge within the test specimen, however, will contribute to voltages of opposite polarity across the LV arms, as the PD current is flowing in opposite directions within $C_k$ and $C_t$.

Polarity discrimination methods take advantage of the effect of opposite polarities of PD pulses within both arms of a PD test circuit.

Figure-2.18 Differential PD bridge (Balanced Circuit)

Figure-2.19 shows two coupling devices CD and CD1, which transmits the PD signals to the special measuring instrument MI, in which a logic system performs the comparison and operates a gate for pulses of correct polarity. Consequently only those
PD pulses which originate from the test object are recorded and quantified. This method was proposed by I.A. Black.

Another extensively used method is the time window method to suppress interference pulses. All kinds of instruments may be equipped with an electronic gate, which can be opened and closed at preselected moments, thus either passing the input signal or blocking it. If the disturbances occur during regular intervals the gate can be closed during these intervals. In tests with alternating voltage, the real discharge signals often occur only at regularly repeated intervals during the cycles of test voltage. The time window can be phase locked to open the gate only at these intervals.

Some more sophisticated methods are used for digital acquisition of partial discharge quantities.
2.10 ORIGIN AND RECOGNITION OF DISCHARGE

Oscillographic studies of discharge patterns have been found to be useful in the qualitative investigation of the origins of the discharges. Some of these patterns may be interpreted with the aid of table given below. The table is helpful in interpreting the origins of discharges. The pattern may indicate the type, size and number of discharging source.

Figure-2.20 Origin and Recognition of Discharges (Part-1)
Figure-2.20 Origin and Recognition of Discharges (Part-2)
### Table-2.1 Interpreting the Origin of Discharge

<table>
<thead>
<tr>
<th>Case</th>
<th>Discharge pattern</th>
<th>Effect of voltage</th>
<th>Effect of time</th>
<th>indication</th>
<th>Display on detection &amp; origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The discharges occur symmetrical on the positive and negative halves of test-wave from. The amplitude is sometime nearly the same on both half cycle but different amounting to 3:1 are normal. There is certain degree of random variation in both amplitude and location of discharge in succeeding cycle.</td>
<td>The discharge magnitude inception is clearly above minimum detectable level. There is little or no variation on discharge magnitude as voltage is raised the extinction voltage is equal to or slightly below the inception voltage.</td>
<td>The time of voltage application usually has little effect.</td>
<td>Internal discharge in a dielectric bond cavity. If a response having greater discharge magnitude occurs at a higher voltage this indicates discharge in second cavity. Typical discharges due to voids in cable insulation.</td>
<td>Figure-2.20 (a)</td>
</tr>
<tr>
<td>2</td>
<td>The discharges occur in advancement of test voltage peaks but are asymmetric. There is a certain degree of random variation in both amplitude and location of discharges in succeeding cycles.</td>
<td>-do-</td>
<td>- do-</td>
<td>Internal discharges between metal and dielectric in a cavity. Typical discharge due to improper adherence of cable insulation with either conductor or screen.</td>
<td>Figure-2.20 (b)</td>
</tr>
<tr>
<td>Case</td>
<td>Discharge pattern</td>
<td>Effect of voltage</td>
<td>Effect of time</td>
<td>indication</td>
<td>Display on detection &amp; origin</td>
</tr>
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<tr>
<td>3</td>
<td>Same as case II except that the number of discharges increase with test voltage.</td>
<td>Same as above except that the discharge magnitude increase steadily as voltage is raised above inception.</td>
<td>-do-</td>
<td>Surface discharges talking place between external metal and dielectric surface typical discharges due to improper end terminations of a cable.</td>
<td>Figure-2.20 (c)</td>
</tr>
<tr>
<td>4</td>
<td>Similar as case I response.</td>
<td>If the voltage is raised to its maximum value, then quickly lowered, the characteristic is similar to for cable I discharge.</td>
<td>The discharge magnitude falls with time but the extinction voltage becomes higher.</td>
<td>The behavior describe has been found in cable insulation containing a cavity in form of fissure in the direction of electric field.</td>
<td>Figure-2.20 (d)</td>
</tr>
<tr>
<td>5</td>
<td>The discharge occur on one half cycle of the test wave form only asymmetrically disposed about the voltage peak and all of them are equal in magnitude and are equally spaced in time.</td>
<td>There is no change in discharge magnitude as the voltage is raised and the magnitude remains constant as the voltage lowered. The extinction voltage coincides with inception voltage</td>
<td>The response is normally unaffected by the time for which the test voltage is applied.</td>
<td>External corona discharge from sharp metal points.</td>
<td>Figure-2.20 (e)</td>
</tr>
<tr>
<td>Case</td>
<td>Discharge pattern</td>
<td>Effect of voltage</td>
<td>Effect of time</td>
<td>indication</td>
<td>Display on detection &amp; origin</td>
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<tr>
<td>6</td>
<td>Coarse and irregular usually unresolved symmetrically distributed about test voltage zeros, but the amplitude is zero near the test voltage peaks.</td>
<td>The magnitude usually increases slowly and proportionally with voltage. It is also observed that it may disappear completely at a particular voltage level and be absent for all voltages above that level.</td>
<td>The response is normally unaffected by the time for which the test voltage is applied.</td>
<td>Contact noise due to imperfect metal to metal joints.</td>
<td>Figure-2.20 (f)</td>
</tr>
<tr>
<td>7</td>
<td>Groups of low frequency oscillations located on the test voltages peaks.</td>
<td>The response is usually undetectable in lower range of voltage &amp; grows rapidly as voltage approaches highest rated voltage of the test transformer.</td>
<td>-do-</td>
<td>Harmonics generated by test transformer core.</td>
<td>Figure-2.20 (g)</td>
</tr>
</tbody>
</table>