CHAPTER 2

DISCHARGE DETECTION

2.1 INTRODUCTION

The primary PD event is a very rapid discharge. The moving electrons and ions in a discharge radiate electromagnetic transients; recombination and de-excitation produce photons. Detection of such signals provides direct information about the discharge. The direct observation of this local phenomena is not possible in insulation systems. The discharges give rise to many phenomena which may be used for detection viz., light, heat, noise, gas pressure, chemical transformations, consequences of electromagnetic radiation and electric phenomena. Dielectric losses and electric pulses are electrical phenomena. Thus PD detection principles are based on the energy conversion process associated with the discharge. Energy conversion based on electrical methods are of prime importance owing to their ability to measure the magnitude and to certain extent the location of discharges. The PD is detected at the terminals of the test object as a tiny voltage drop (Kreuger 1964 Jarle 1996) which is of the order of micro volts to milli volts. To be recognised as PD, the current induced in the external conductor must be sufficiently large enough to be detected and must occur with sufficient rate to be recognisable as something other than random noise. PD detection and measurement were not needed at the time when paper insulation was paramount. In paper-based insulation either no cavities or hundreds or thousands of tiny cavities at a time break down recurrently under the effect of alternating current voltages. No special detection methods were needed as the integrated losses of all these discharges would easily be detected by means of loss measurement with a
Schering bridge. The measurement of PD generally relies on the detection of electrical pulses in a high voltage circuit. The sensitivity of measurement is limited by the background noise and it is the presence of such electrical noise that causes most of the problems with PD measurement. Hence utmost care is taken to **design and construct a detector that can be switched between narrow-band and wide-band for PD data acquisition**. This chapter explains the development of PD on a simple insulation arrangement, the difficulties encountered while detecting the feeble PD signals, the design and implementation of a detector. **Conventional display processing like, direct displays and meter displays are used for classical characterisation of PD. Computer driven displays are preferred for the ease with which relevant information on the intricacies of the PD behaviour as a function of time can be stored. Further information processing may yield data concerning the life expectancy dependence on PD onset and long term stability.** Present stress prevailing on quality assurance of manufactured equipment with latest technology demands the use of computerised discharge analysers for analysing both the shape and the sequence of PD pulses for meaningful interpretation. A comparative analysis of various display processing is made. Advantages and disadvantages of each display processing method along with their applications are listed out. This also reports the development of a **VXI based PD acquisition system with graphical programming** and its special features allowing the users to spend less time on input-output implementation (major hurdle faced by a programmer) in development environment and more time in analysing the results. Hence better and meaningful interpretation of PD data are achieved.
2.2 BASIC PD DETECTION CIRCUIT

This section explains the development of PD on a simple insulation arrangement. The advantage of equivalent circuit diagram of discharge process is that fairly elementary circuit analysis can be used to explain in principle the nature of the signals that appear in a PD measuring circuit (IS 2071 1974 & 1976).

2.2.1 Equivalent circuit diagram

The following discussions assume the presence of a small defect (cavity or void) in a solid or liquid insulation material (Kuffel and Zaengl 1984). In the equivalent circuit diagram (also popularly known as a-b-c model) shown in figures 2.1a&b, $C_c$ represents the capacitance of the cavity in the dielectric. Capacitors $C_b'$ and $C_b''$ take into consideration the field lines that emanate from the electrodes and end in the cavity and their series connection leads to the capacitance $C_b$. The fault-free component of the test object is represented by the elements $C_a'$ and $C_a''$ respectively. The following formula always applies to small cavities expressing the test capacitance ($C_t$):

$$C_t = C_a' >> C_c >> C_b$$

(2.1)

When the voltage applied increases beyond the breakdown voltage of the cavity capacitor $C_c$, the discharge gap $F$ acting as a voltage-sensitive switch breaks down and discharges capacitor $C_c$ through resistor $R_1$. The latter limits the amplitude of the discharge current $i_1(t)$. The duration of such a discharge process is in the nanosecond range. The voltage drop $\Delta V_1$ at the cavity caused by the discharge current $i_1(t)$, releases a charge $\Delta q_1$.

$$\Delta q_1 = \Delta V_1 \cdot C_c$$

(2.2)
Figure 2.1 Formation of Partial Discharges
It should be noted that \( i_1(t) \) is a local current that cannot be measured. The discharge of \( C_c \) also causes rapid charge transfer in capacitors \( C_b \) and \( C_a \) of the equivalent circuit diagram. The resulting voltage drop \( \Delta V_t \) across the terminals AB of the test object can be computed. The magnitude of \( \Delta V_t \) can be determined by comparing the stored charge before and after the discharge process.

\[
\Delta V_t = \left[ \frac{C_b}{C_b + C_a} \right] \quad \Delta V_1 = \left[ \frac{C_b}{(C_b + C_a)C_c} \right] \quad \Delta q_1
\]  

(2.3)

Based on empirical estimates for \( C_b \) and \( C_a \), the values for \( \Delta V_t \) are in the range of millivolts to Volts while the magnitude of \( \Delta V_1 \) is in the kilovolt range. The voltage drop \( \Delta V_t \) cannot be related to the quantities \( \Delta V_1 \) and \( \Delta q_1 \) at the fault location because the capacitances \( C_c \) and \( C_b \) are normally unknown.

2.2.2 Basic PD test circuit

The test object viewed from terminals AB (Figure 2.1b) is in reality always connected to a voltage source and a coupling capacitor \( C_k \). The voltage drop \( \Delta V_t \) is now more or less compensated by a measurable current \( i(t) \). This current occurs as a circular current (Figure 2.2) for high-frequency processes and the voltage source is usually decoupled by impedance \( Z \) from the actual test circuit formed by \( C_t \) and \( C_k \). For this reason, high frequency interference currents from the voltage source can only partially flow into the test circuit.

As can be seen from figure 2.2, the short-duration circular current \( i_{-t} \) and \( i_{-k} \) in the capacitors show a phase displacement of nearly 90 degrees relative to the sinusoidal voltage \( V_t \). The PD currents \( i(t) \) are superimposed on these power-frequency currents with strong magnification in the form of small peaks. It should be noted that the PD currents in capacitor \( C_k \) and
Figure 2.2  Partial Discharge pulses and displacement currents
$C_t$ have different polarities but their amplitudes are always identical (neglecting stray capacitances). The pulse rates do not follow any theoretical principle and vary randomly. Within a half-wave of the alternating current supply system one or several PD pulses can occur, depending on the magnitude of the test voltage and the characteristic of fault location. If a test object has several fault locations, more PD pulses will occur in intervals of a few microseconds to nano seconds. In general the greatest discharge rate is observed during the largest voltage variation $dV_t/dt$. Thus, the pulse polarity does not depend on the polarity of the test voltage $V_t$ but only on the sign of the voltage variation $dV_t/dt$. In contrast, corona discharges (external PD) appear typically in the apex of the applied test voltage and the sign of the pulse corresponds to the sign of voltage $V_t$.

2.2.3 Definitions of apparent and measurable charge

The magnitude of the measurable PD circular current $i(t)$ depends on the capacitance ratio $C_k/C_t$, because the charge is removed from capacitor $C_k$ for compensating the voltage drop $\Delta V_t$. In the ideal case $C_k \gg C_t$ and the charge '$q$' transported by $i(t)$ is the greatest, i.e.

$$q = \int i(t) \, dt = \left[ C_a + \frac{C_c}{C_c + C_b} (C_c + C_b) \right] \Delta V_t \quad (2.4.a)$$

In practice $C_c \gg C_b$ and $q$ is simplified as shown below:

$$q = (C_a + C_b) \, \Delta V_t = C_t \, \Delta V_t \quad (2.4.b)$$

Substitution of the equation 2.3 in 2.4.b leads to the following expression

$$q = C_b \, \Delta V_t = \frac{C_b}{C_c} \, \Delta q_t \quad (2.5)$$

Charge 'q' is referred to as the "apparent charge" of a PD pulse.
In practice the condition $C_k \gg C_t$ is never satisfied as a large coupling capacitor will too heavily load the voltage source and also it is not viable. However, a capacitor that is only a little larger than the capacitance $C_t$ of the test object results in reduced sensitivity because the compensating current $i(t)$ becomes smaller. Taking the charge transfer process between capacitors $C_t$ and $C_k$ into consideration, following relationship is obtained:

$$q = C_t \Delta V_t = (C_t + C_k) \Delta V'_t$$  \hspace{1cm} (2.6)

where $V'_t$ represents the residual voltage drop after the charge transfer. The charge released by the coupling capacitor can now be measured and is consequently referred to as the measurable charge $q_m$ given by,

$$q_m = C_k \Delta V'_t$$  \hspace{1cm} (2.7)

The ratio of measurable to apparent charge can thus be defined as

$$\frac{q_m}{q} = \frac{C_k}{(C_t + C_k)}$$  \hspace{1cm} (2.8)

The significance of this equation is illustrated in figure 2.3. The ratio $q_m/q$ is an essential quantity for the measuring sensitivity in PD testing. For sensitive measurements, a sufficiently large coupling capacitor should be installed, depending on the capacitance $C_t$ of the test object. Ratio $q_m/q$ and the attainable measuring sensitivity can be easily verified by calibrating the test circuit (Gallagher 1983).

2.2.4 Measurement of the pulse currents

Although direct detection of short-duration PD current pulses is usually not performed in practical applications, such measurements can frequently supply important information concerning the discharge processes
Figure 2.3 Influence of coupling capacitor on the measuring sensitivity
in a test object. The time characteristic of an electric discharge depends strongly on the nature of the fault and the design of the entire insulation arrangement. The shape of measurable current pulse $i(t)$ (circular current) depends on the physical discharge process at the fault location in the test object. The principle of PD current measurement is shown in figure 2.4. The function of the high-pass amplifier installed direct at the measuring resistor is to suppress the power-frequency current $i_L$ and to further amplify the short-duration current pulses.

Assuming a short-duration PD current pulse the voltage $V_m(t)$ is calculated as per the following equation:

$$V_m(t) = \frac{q}{C_s + C_t(1 + \frac{C_s}{C_k})}\exp\left(-\frac{t}{\tau}\right)$$

(2.9)

where $\tau$ is the time constant of the circuit as shown below:

$$\tau = R_m \left( C_s + \left( C_t C_k \right) \left( C_t + C_k \right) \right) 621.3$$

(2.10)

The voltage $V_m(t)$ at the measuring resistor $R_m$ indicates a fast rise (ideally a voltage step) which is followed by an exponential decay with the time constant. The circuit elements obviously have completely deformed the original pulse, at least with respect to the decay of the signal. Pulse current measurement on large high voltage equipment and installations frequently leads to highly complex time characteristics of the signals. Direct detection of the time characteristic of such current pulses requires not only relatively sophisticated measuring techniques but also a high degree of experience in interpreting the measuring results. As a consequence, the current pulses today are integrated in all routine inspections and the PD processes are interpreted based on the measured or the apparent charge. Integration of highly diverse current pulses is accomplished in 'narrow-band' and 'wide-band' measuring systems, where the wide band and narrow band measuring
Figure 2.4 Principle of pulse current measurement

$R_m = 5 \ldots 100 \, \Omega$

$C_s = 0 \ldots 10 \, \text{pF (STRAY CAPACITANCE)}$

Figure 2.4 Principle of pulse current measurement
systems are taken in the contest of the band pass systems with respect to amplification.

2.3 INTEGRATION USING FILTER SYSTEMS

Low pass and band pass systems can be used for integrating PD currents. The signals of interest (PD pulses) are small pulses superimposed on large power frequency voltages; successful detection of the pulses requires separating these pulses from the power frequency voltages. Integrating PD currents is best understood using frequency spectrum of PD pulses.

For a given non-periodic current pulse \( i(t) \), the complex frequency spectrum \( I(j\omega) \) is obtained from the Fourier integral and is given by,

\[
I(j\omega) = \int_{-\infty}^{+\infty} i(t) \exp(-j\omega t) \, dt \quad (2.11)
\]

The amplitude spectrum \( I(\omega) \) is given by

\[
I(\omega) = |I(j\omega)| \quad (2.12)
\]

It is already discussed that the measurable PD pulse current \( i(t) \) can be shaped quite differently. In a first approximation, the time characteristic of the pulses is represented by a decaying exponential pulse expressed by \( i(t) = I_0 \exp(-t/\tau) \). The apparent charge 'q' transported by this idealised current leads immediately to the following identity :

\[
q = \int_{0}^{\infty} i(t) \, dt = I_0 \tau \quad (2.13)
\]
According to equation (2.11), the complex spectrum of the exponential pulse depends on the angular frequency $\omega$. Substituting $\omega = 2\pi f$ in equation (2.12), the desired amplitude spectrum $I(\omega)$ is obtained.

$$I(\omega) = I_0 \frac{\tau}{\sqrt{(1+2\pi f\tau)^2}} = \frac{q}{\sqrt{(1+2\pi f\tau)^2}}$$  \hspace{1cm} (2.14)

For better comparison, the amplitude spectrum shown in figure 2.5 is illustrated in normalised form by relating $I(\omega)$ to the value $I(\omega = 0)$ which is obtained for frequencies $f \rightarrow 0$. It clearly shows that the 'DC content' in the spectrum corresponds to the pulse charge $q$. This statement according to the exponential pulse will hold for any pulse shape $i(t)$ which can be readily derived for $\omega \rightarrow 0$ from equation (2.11).

For sufficiently low frequencies, the spectrum of any PD pulse $i(t)$ contains the complete information concerning their time integral (charge 'q'). A measuring system responding to DC components of the spectrum can consequently integrate the PD currents.

### 2.4 NOISE SOURCES AND THEIR SUPPRESSION

In practical work, sensitive PD tests are aggravated by different noise sources. The various measuring systems for detecting the apparent charge differ in their ability to suppress certain noise sources. Before covering such systems in more detail it is necessary to recognise the main sources of interference. The power-frequency displacement currents $i_{\text{L}}$ and $i_{\text{K}}$ are major sources of interference during detection of very small PD pulses. Depending on the values of $C_k$ and $C_L$, these currents range from a few milli amperes to several amps. It is, therefore, necessary to filter such short-duration PD pulses effectively out of these quasi-stationary currents. Figure 2.6 shows typical noise sources indicated by numerals 1 through 11. Difficulties are encountered frequently in the generation of high-voltages or
Figure 2.5 Decaying exponential pulse
the operation of the circuits since the power supply (1/11) as indicated in figure 2.6 itself is a major noise source due to higher harmonics in the mains and periodic pulse currents of thyristor-equipped controls. Sliding contacts of variable-ratio transformers or carbon brushes of a generator (2) can lead to high-frequency pulse interferences that are transmitted by transformer (3). Such interferences on the high-voltage side can effectively be filtered by high voltage filter (4), provided no additional noise is generated by an incorrect rating of the filter. All sharp edges, points, and rough surfaces on connecting lines and stress control electrodes (5) lead to corona discharge. Isolated metallic particles (7) within the test area will be charged to high potential in the electric field. Excessive field strengths lead to a pulse-like discharge that is coupled into the high-voltage circuit in the form of interference. Similarly, switching phenomena (8) in adjacent low-voltage and high-voltage networks and harmonic signals from radio transmitters (9) in the long and medium wave band enter into the test circuit.

To summarise, the interferences can be classified as follows:

**Pulse-shaped noise**: These are mostly of stochastic in nature and are of short duration, the spectrum of which cover a correspondingly large frequency range.

**Harmonic interference**: These are due to power controllers (thyristor circuits) and mains harmonics; the signals appear in the frequency spectrum as a multiple of the mains frequency. Radio transmitters in the long and medium wave band induce harmonic currents in the measuring circuit on selected frequencies.

Pulse-shaped noise in the PD test circuit are basically detected by a measuring system in the same manner as 'genuine' PD signals. When
Legend

1/11 Power supply
2 Variac or Voltage regulator
3 High voltage source
4 Filtering of High Voltage source
5 Feeder line and electrodes
6 Coupling capacitor
7 Loose conductive objects in the vicinity of the test location
8 Pulse-shaped interferences
9 Electro magnetic waves by radio transmitters (harmonic interferences)
10 Interference currents in ground system of PD measuring instrument

Figure 2.6 Typical noise sources
sensitive measurements are conducted, recognition and elimination of
individual noise sources are consequently of great importance. Some useful
aids in the form of detailed 'diagnostic instructions' (CIGRE 1969 & 1972)
are available. If a screened test laboratory (Faraday cage) is available for
measurements many 'external' noise can be kept away from the test circuit.
In a favourable test setup, the attainable measuring sensitivity depends only
on the type of PD measuring system used and the characteristics of the test
object. If PD measurements are conducted in an open or insufficiently
screened test shop, the measuring sensitivity is largely influenced by the
level of ambient interference. To ensure that measurements with sufficiently
high sensitivity are possible, additional noise suppression is required. In
many cases this can be accomplished with the aid of a balanced circuit
(Praehauser 1973).

2.5 PULSE DETECTOR

The traditional RIV detectors and the loss detectors are incapable
of detecting large pulses mixed with a background of other smaller PD
pulses. Hence they are not of much use. Pulse detection is a right choice,
because it is possible to observe pulse shape along with pulse polarity.
Circuits according to IEC are used for measuring partial discharges and the
apparent charge is detected.

2.5.1 Straight Detection Technique

The straight detection method for detecting PD pulses utilises a
coupling capacitor that is placed in parallel with the test object and the
discharges are measured across an external impedance (IEC 270 1981 & IS
6209 1982). After band limiting and amplification, the output response to a
discharge current pulse is a fast oscillatory signal with its peak value
proportional to the discharge amplitude.
The typical pulse detection network is implemented using a high-voltage capacitor terminated by a measuring impedance. Most commercial measuring impedance networks, also known as Power Separation Filters (PSF), can be modelled as a RLC network as shown in figure 2.7. Stray reactance and non ideal components influence the response of these networks, but their primary behaviour can be modelled as the second order response of a RLC network, even in the case where a transformer is used in place of the inductor. Broad band pulse detection is by far the most common method for measuring PD and many standards specify its use. Using broad band pulse detection systems, the operator can directly observe the pulse shape along with pulse polarity which is not possible with narrow-band systems (IEEE Guide C57.113-1991).

The input capacitor in the circuit is the high-voltage coupling capacitor which must be partial discharge free up to the maximum test voltage of the system. The capacitor \( C_M \) is included to modify the transient response of the network, but sometimes it is small and just represents a stray capacitance. The inductor has a low impedance at power frequencies so that the alternating current excitation voltage is eliminated as a voltage drop across \( C_t \) (Figure 2.7).

The selection of the capacitor, inductor and termination resistor determines the frequency (and transient) response of the network. When combined with the source impedance of the device under test, the elements in the power separation filter determine whether the response is narrow-band or broadband. In general, the networks used in practice are damped so that the oscillations in the transient response die out rapidly, which means that these filters are broadband.

The sensitivity of the detection system varies inversely with the capacitance of the device under test. Increasing the power separation filter
Figure 2.7  Modelling of pulse detector network as a RLC network
capacitance increases the sensitivity. In some applications, the device under test is used as the input capacitor to the power separation filter to reduce the system cost. In this situation, the other components in the power separation filter must be rated to handle the large charging currents of the device under test and must be able to withstand large transients during failure of samples.

The external impedance usually consists of a resonant circuit. One function of the resonant circuit is to expand the discharge current pulses in the time domain so that they are easier to detect. This arrangement has several inherent advantages. Firstly, a known pulse can be injected into the resonant circuit in order to calibrate the system. Secondly, the optimum sensitivity can be obtained by maximising the ratio of the coupling capacitance to the capacitance of the test object. Combined with the frequency response of the amplifier which is selectable, the effective bandwidth of the whole detection system is either narrow, medium (also called beta) or wide-band (alpha). The narrow-band response is highly oscillatory which gives poor resolution. With the other two responses which are more commonly used, the waveform is a decaying signal but with much less oscillation, i.e. highly damped. For an alpha waveform, the first peak is greater in magnitude than the succeeding peaks. It is the pulse carrying information regarding the amplitude and polarity of the discharges. With a beta waveform, the second peak is the largest one and it carries the discharge information. The remaining pulses within the waveform do not serve any useful function and make the task of extracting the discharge information much more difficult. The duration of complete waveform associated with a single discharge is variable. It is affected by the signal magnitude which in turn is dependent on the discharge level and the amplifier gain. A large signal has more oscillations and takes longer time to decay. Typically it varies around 50 µs which is called the dead time. If successive PDs occur within the dead time, superimposition of waveforms
could lead to cancellation or magnification of the discharge signals and give false readings. Narrow band measuring systems have long time constants. They detect and integrate the detected PD signals. Individual pulses appear only as an average value.

2.5.2 Resolution

When all the discharges present cannot be separately resolved, there is an error of measurement. This is due to the fact that a number of discharges combine to give a single response of obviously a wrong value as it is not known how many pulses have been combined into one pulse. Wide-band detectors have a much better resolution and are less susceptible to this error. As the error leads to a measured value of discharge magnitude which is higher than the true value, it is on the safe side. As the number of discharges is usually small at the inception voltage errors of this type are unlikely. The object of the test is to determine inception voltage or to prove that the sample is discharge free at a specified test voltage.

2.5.3 Direction

Wide band detectors indicate the direction and also measure the magnitude of discharges. This makes it possible to discriminate between discharges in the sample and those in the coupling capacitor. It is also possible to discriminate between discharge in terminations and those in the sample. As examination of the fine detail and propagation characteristics of the individual PD pulses is required a system with even wider band widths is preferred and used. Integration of short duration PD current pulse is performed using a system that can be switched between 'narrow-band' and 'wide-band'. A comparison of both the techniques is delineated in table 2.1.
2.5.4 Bandwidth Selection

Depending on the device under test and choice of network components, the power separation filter can behave like a high pass or band pass filter. When power separation filter is used along with distributed parameter systems, it behaves like a high pass filter ($C_m$ nearly zero). When it is used with lumped capacitive devices it behaves like a resonant RLC circuit with low quality factor. The power separation filter components primarily determine the lower cutoff frequency of the network, but the lower cutoff can also be influenced by the device under test. The device under test also influences the upper cutoff frequency.

Table 2.1

A Comparison Of Narrow-Band And Wide-Band Systems

<table>
<thead>
<tr>
<th>Features</th>
<th>Narrow-band system</th>
<th>Wide-band system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>9 kHz (-6dB values)</td>
<td>50 - 350 kHz (-3 dB values)</td>
</tr>
<tr>
<td>Centre frequency</td>
<td>variable 50 kHz-2 MHz</td>
<td>variable : 50, 90, 130 kHz lower cutoff frequency ; 160, 215, 350 kHz upper cutoff frequency</td>
</tr>
<tr>
<td>Noise sensitivity</td>
<td>low</td>
<td>relatively high</td>
</tr>
<tr>
<td>Max. admissible PD pulse width</td>
<td>depends on selected centre frequency</td>
<td>approx. 1 μs</td>
</tr>
<tr>
<td>Pulse Resolution time</td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td>Pulse Polarity</td>
<td>not detectable</td>
<td>detectable</td>
</tr>
</tbody>
</table>
Other filtering within the instrument is used to control both the upper and lower cutoff frequencies. The cutoff frequencies, in turn, determine the band-width, which varies with applications and is usually less than 250 kHz. The lower cutoff frequency of pulse detector is greater than 20 kHz.

The cutoff frequencies and transient behaviour of the detector are a compromise that depend on a number of factors. Standards and test specifications mandate the time domain behaviour of detectors by imposing requirements on the pulse resolution. This requirement is stated in terms of the maximum error caused by superposition of closely spaced pulses. These requirements determine the transient response of the pulse detection network and filters used in the instrument. Another factor that influences the choice of the lower cutoff frequency is the need to eliminate low frequency conducted interference, such as harmonic distortion in the power source and switching noise (Steiner 1991). The upper cutoff frequency is chosen taking into account the interference caused by AM radio broadcasts. The choice of the measurement band is also a compromise between the desire for higher sensitivity (increased bandwidth) and a desire to minimise the variability of the measurement caused by frequency dependent attenuation with the device under test (decreased bandwidth). Hence a lower cutoff frequency of 50 kHz and an upper cutoff frequency of 340 kHz are chosen.

2.5.5 Detector Network

A broad band detector using pulse detection network as shown in figure 2.8 is designed and fabricated. An upper cutoff frequency of 340 kHz and a lower cutoff frequency of 50 kHz are fixed as mentioned earlier. A band-width of maximum 300 kHz is obtained by cascading a second order low pass Butterworth filter and a second order high pass Butterworth filter as shown in figure 2.9.
Figure 2.8 Partial Discharge detector
Figure 2.9  Second order bandpass Butterworth Filter
The special advantage of the active circuitry for use in filters is the interesting fact that inductors can be totally avoided (availability of operational amplifiers in the integrated form). The band pass filtering provided by the RC combination forming 340 kHz low pass filter and by the RC combination forming 50 kHz high pass filter are shown in figure 2.10 and 2.11 respectively.

\[
\text{Cutoff frequency } f_c = \frac{1}{2\pi RC}
\]  

(2.15)

To get the desired \( f_c \), the values of \( C \) and \( R \) are chosen to be 0.01 µf and 47 Ω respectively. The value of \( f_c \) works out to be 340 kHz.

Before conducting the actual experiments the performance characteristics of the detector are checked. A sine wave of known peak to peak magnitude from a function generator is given as an input to the detector and an output is obtained from the detector at different frequencies. The frequency response plot is obtained. The bandwidth of the detector is found to be well above 300 kHz.

The Fast Fourier Transform (FFT) which is a powerful tool to perform the frequency domain analysis (Witte 1991) is effectively used to compare the performance of the detector. The different frequency components of the detected signal are separated as shown in figure 2.12 with sampling rate of 50 Mega samples per second (Msa/s), a centre frequency 300 kHz and a frequency span of 600 kHz. The peak variation at 320 kHz is found to be 27.5 dB. From the frequency response characteristics the peak variation is found to be 26 dB. The error is found to be 3.3%, which is within the tolerance limit (IEC 270), indicating the validity of the design of the wide band detector designed and implemented.
Figure 2.10  Second order lowpass Butterworth Filter

Figure 2.11  Second order highpass Butterworth Filter
Figure 2.12 Frequency response of the detector
The gain of the amplifier is 1000 and it can be varied. The bandwidth can also be varied. A selector switch is provided for the same. The fact that the signal processing may lead to a wrong interpretation is explained referring to the figures 2.13 and 2.14. Figure 2.13 describes how the band limiting affects the interpretation of recording when the discharge level is maintained constant. The peak discharge magnitude seems to take different values as shown in figure 2.13. Figure 2.14 describes how the sampling time of the recorder influences the interpretation of PD data. It has been found by trial and error that the sampling rate of 200 kilo samples/second satisfactorily reproduces the PD pulses and a band-width of 500 kHz improves the digital storage and interpretation. The detector, taking care of the variation of the sampling time depending on the signal to be captured, is an integral part of the PD data acquisition system. Quantisation and recording of the basic discharge parameters are also done using an oscilloscope for further analysis. A 10 bit, 100 MHz, 20 Mega samples per second digital storage oscilloscope is used as a direct display mode.

2.5.6 Display Processing

Three types of displays are possible and are listed as follows:

♦ meter display
♦ direct display
♦ computer driven display
Figure 2.13 Effect of band limiting on interpretation
Figure 2.14 Effect of sampling time on interpretation
Meter displays are implemented using either a digital panel meter or an analog meter movement and display a number related to some parameter of the partial discharge process. Meter displays are often associated with integrated measurements and are commonly used in simple partial discharge detection systems. More sophisticated detection systems use meters as auxiliary display devices so that several parameters can be monitored simultaneously.

Instruments with direct displays operate in the same manner as an oscilloscope. The detected pulse is displayed directly on a CRT. Direct displays use different time base modes. The most common is the elliptical time base mode in which the partial discharge pulses are displayed around the perimeter of an ellipse as shown in figure 2.15. The positions around the ellipse correspond to the phase of the high voltage excitation. Another popular method is the linear time base in which the PD pulses are displayed along a straight line or a sinusoid as shown in figure 2.16. One of the advantages of the direct display approach is that signatures of different types of PD are easily recognised by a skilled operator.

The description 'computer driven display' conveys the information that the system is digital, and with present day technology, this offers limitless avenues for analysing PD. This method requires that the detected PD pulse be digitised either into a value(s) (Table 2.2) or a waveform. Typical applications process the data and compile measured results into tabulated/graphical form for display (Figure 2.17) on a computer screen. In principle, this display mode can perform any of the functions of the direct displays and meter displays except real-time display of the pulses.
Figure 2.15 PD display patterns - Sinusoidal representation

Figure 2.16 PD display patterns - Elliptical representation
Figure 2.17 Integrated PD quantities
Table 2.2
Numerical representation of basic discharge quantities

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Degree</th>
<th>Sign</th>
<th>Magnitude in nano Coulombs</th>
<th>Energy in nano Joules</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>108</td>
<td>-</td>
<td>1.324</td>
<td>17.807</td>
</tr>
<tr>
<td>0</td>
<td>258</td>
<td>-</td>
<td>2.299</td>
<td>31.807</td>
</tr>
<tr>
<td>1</td>
<td>32</td>
<td>-</td>
<td>1.73</td>
<td>12.969</td>
</tr>
<tr>
<td>1</td>
<td>24</td>
<td>+</td>
<td>1.12</td>
<td>6.44</td>
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<td>314</td>
<td>+</td>
<td>1.352</td>
<td>13.753</td>
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</tbody>
</table>

#### 2.6 CALIBRATION

While PD measurement detectors use extremely sensitive measuring circuits, they are uncalibrated and each time the measurement system is used, it must be calibrated using special methods. The need for calibration is derived from the fact that the relative proportion of charge transferred to the detector changes with the circuit parameters of the device under test. This can be seen by considering the change in voltage division among the circuit elements. Even if the parameters of the device under test are the same, changing the geometrical arrangement of the test system changes the stray capacitances which in turn changes the proportion of...
charge transferred to the detector. For these reasons, the system must be calibrated with the device under test connected and in the exact configuration to be used during the test. Several methods are used for calibrating the test system: the low voltage direct method, the high voltage direct method and the indirect method. All the methods are fundamentally similar. A step voltage, $V_0$, is applied to the device under test through a calibration capacitor, $C_0$, yielding a charge of $V_0 \times C_0$ Coulombs. The high voltage direct method uses a high voltage calibration capacitor connected in parallel with the specimen which remains connected to the system during the test and measurement and is shown in figure 2.18. The low voltage direct method uses a low voltage capacitor that is connected to the test system only during calibration and is removed during testing. The indirect calibration method is performed through the power separation filter coupling capacitor. Both the low voltage direct and the indirect calibration methods introduce errors which necessitate the use of correction factors (IEEE Std. 454 and IEC 270). Correction factors are based on several capacitances in the system, including the specimen capacitance, coupling capacitor, calibration capacitor and stray capacitances which are usually known. The high voltage direct method has the advantage that no errors occur during calibration; however, high voltage PD free calibration capacitors are expensive. While direct high voltage calibration is preferred, difficulties using direct low voltage and indirect calibration occur only when the specimen capacitance is small.

2.7 TRADITIONAL CHARACTERISATION OF PD ACTIVITY

The classical way of evaluating discharges in gas insulated switchgear or in other insulation constructions is to determine the inception voltage (in kV), which is the lowest voltage at which the discharges of a specified magnitude start to occur in successive cycles when an increasing
Figure 2.18 Calibration of test circuit
alternative voltage is applied to the insulation. The largest discharge present (in pC) is also to be determined and compared with the test specifications.

The apparent charge, the widely popular PD quantity is the only value representing the PD given (ASTM 1981). Being measurable in a simple way, this measurement is very popular for the following reasons.

♦ 'q' is directly related to the energy in the discharge.
♦ 'q' is directly related to the size of the defect.
♦ 'q' can readily be measured.

It can be shown that the harmfulness of a discharge is related to the order of magnitude of 'q' in powers of ten. Commercial quality assurance is mainly decided by this measure. Table 2.3 gives the conventional or classical characterisation of discharge levels in case of a 11 kV current transformer.

Table 2.3

Conventional or Classical Characterisation of Discharge Levels

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Apparent charge measured with Wide band system - pC</th>
<th>Apparent charge measured with narrow band system - pC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100 to 200</td>
<td>130</td>
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<td>2</td>
<td>300 to 400</td>
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<td>60</td>
<td>52</td>
</tr>
<tr>
<td>8</td>
<td>90</td>
<td>86</td>
</tr>
</tbody>
</table>
2.8 CASE STUDIES

2.8.1 Case Study 1 - Current Transformers:

A 11 kV current transformer is considered for quality assurance. Its solid insulation is evaluated by the measurement of 'q'. Table 2.4 reveals the permissible discharge levels. Measurements are taken with the coupling capacitor whose value is 1 nano farads and tuning capacitor of value 50 pico farads. Background noise level is 2 pC.

Table 2.4
Permissible Discharge Levels

<table>
<thead>
<tr>
<th>Permissible Partial Discharge level</th>
<th>Apparent charge of 250 pC at 1.1 Vm/\sqrt{3}. Prestress voltage of 1.3 Vm for 10s for a system with an effectively earthed star point.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Apparent charge of 50 pC at 1.1 Vm Prestress voltage of 1.3 Vm for 10s for a system with isolated or resonant star point.</td>
</tr>
</tbody>
</table>

where Vm is the highest system voltage. This value for solid insulation is 7.2 kV per mm (IS 11322 1985).

The current transformers tested belong to the same batch with similar specifications. Samples 2, 3 and 4 have discharge levels greater than the permissible values whereas others are within the test specifications. Prestress voltage of 16.36 kV (1.3 x 7.2) was applied for 10 seconds and
all withstood the stress for a time duration of 10 seconds; the discharges were found to be within the permissible values.

2.8.2 Case Study 2 - Surge Arrestors

Surge arrestor specimen of same batch with similar specifications were considered; the PD test was done during manufacturing. The test revealed that the discharge levels shot up to a very high value of 200 pC, whereas permissible levels are well within 50 pC. The pieces with such high values were again reassembled after tightening of the screws, making proper contacts, refitting etc. A considerable reduction in the discharge level was noticed. In case of specimens which again showed higher discharge levels, the internal blocks were exchanged for better quality and further testing showed lower permissible discharge levels. This is due to the removal of defective insulation, bad contacts and thereby avoiding internal discharges and surface discharges. Discharge levels due to internal discharges were found to be less when compared to discharge levels due to surface discharges.

2.9 LIMITATIONS OF CLASSICAL CHARACTERISATION

The deterioration process due to discharges within an insulation system is certainly a result of all discharges and is not limited to the maximum values only. Much recent work has been related to the measurement of all PD pulses and to the evaluation of the results on a statistical basis. Depending upon the extent of the detection and analysing systems, the number of pulses, the pulse intervals and the amplitudes of the individual pulses may be detected. The large amount of information available by the great number of events (Wooton, 1987) and the distributions have characteristic shape which vary with the type of the defect (CIGRE 1969 & Gulski 1994). Only a few basic discharge quantities
can be measured and it is difficult to achieve good accuracy where discharge activity is not steady. Accumulated knowledge based on past experience is essential to correlate the different discharge patterns with the type of defect. Even so, subtle changes in the pattern which may indicate a potential deterioration in the insulation system can not be easily recognised. The physical process is not reflected adequately by the apparent charge evaluation (James 1991 Phung 1992 & 1993). Methods, either characterising the cause of the PD (the holes or protrusions etc. and the electrical field distribution) or the PD reaction products are often not applicable and also expensive. Alternative methods (example-acoustical) can sometimes detect and localise but not identify the PD source.

It seems important to correlate the apparent charge and derived PD quantities with direct measurable stress or related factors in order to get more and immediately connected indicators. The advances in Computer Technology make it possible to process high amounts of actual data and evaluate the due correlations.

Measurement of basic discharge parameters associated with each individual PD pulse include the discharge pulse magnitude, polarity, its phase position relative to the power frequency and the applied test voltage. Based on these basic quantities, a wide range of analyses can be implemented with appropriate computer programs.

A simple analysis is to calculate the deduced or integrated quantities such as those recommended by the IEC Standard. These integrated quantities can be used to replace the large amount of raw discharge data. Only few parameters are required to describe the discharge activity over a period of time. In some cases, these parameters are adequate for assessment of the insulation integrity. However, minor variations in
the discharge pattern which possibly indicate a potential deterioration in the insulation system can not be easily detected with this technique.

More sophisticated techniques are based on phase-resolved analysis (Kreuger 1992 & 1993). The discharge pattern over a period of time is governed by three variables; pulse amplitude 'q', its relative phase occurrence 'φ' and the pulse count 'n'. It is well-known that different types of insulation defects generate different discharge patterns. If these differences can be captured in a knowledge base (Cachin 1995), the inference on the type of defect from the observed PD pattern is possible. This makes possible the realisation of an expert system which eliminates the reliance on operator knowledge to interpret the PD patterns. One approach is to apply standard statistical analysis to calculate the statistical moments of the univariate distribution.

2.10 COMPUTER DRIVEN DISPLAYS

In order to store as much information as required on the intricacies of the PD data, collection and analysis of huge volumes of data are essential. Hence computerised analysis is a must. The following section discusses one typical computer driven display processing used in this work.

2.10.1 The CDA3 System

A unique feature of this analyser - computerised discharge analyser (CDA) - is that the complete history of the discharge activity for every individual PD pulse can be recalled for investigation.

This system is a total custom built hardware solution to replace both the Digital Storage Oscilloscope and the signal processing software needed for extracting PD information (James 1991 Mukherji 1995).
Interfacing between the CDA3 and the PC is through a 16 bit digital input/output bus with direct memory access (DMA) capability. There are two analog input signals to the CDA3. One is the 50 Hz reference signal from a high voltage resistive divider in parallel with the test object. This is fed into a timing circuit which divides each half cycle into 1000 phase windows, i.e., the phase resolution is 0.18 degree. Another circuit measures the average value of the 50 Hz signal. Proper scaling ensures that the digitised value is equal to the rms value of the applied test voltage with a resolution of 0.1 kV. This information is sent to the PC once in every fifty cycles. To avoid memory conflict between test voltage and PD signals, a 10 micro seconds window blocks out PDs which occur during the transmission of the test voltage. This window is negligible compared to the one second interval. Furthermore, it is timed to coincide with the zero crossing where the presence of partial discharges is not usual.

The other analog input is the signal from the detector amplifier. After rectification, it is fed into a level detector. If the signal exceeds a preset threshold which is adjustable depending on the amount of background noise, a discharge is considered to be present. This in turn activates a 20 micro seconds window, long enough for a peak and hold circuit to capture the largest peak in either the first or second pulse. Depending on the response (alpha or beta), the discharge polarity can be derived based on the polarity of the first pulse (same or complement) from the unrectified signal. Also within this time window, the phase position information is transferred to the PC. As the period expires, a high speed 10 bit analog to digital converter (3 micro seconds conversion time) digitises the discharge magnitude. This completes the data acquisition and transfer process of pulses which occur well within the dead time so that the system is ready for new discharges. The variable dead time is monitored using retriggerable monostable oscillator to generate a dynamic window following the fixed 20 micro seconds window. This blocks out the remaining oscillation
in the wave form and remains active until the signal level stays below the threshold level for at least 20 micro seconds.

The use of circular memory buffer for data transfer under DMA is a novel feature of the CDA3. With a conventional linear buffer the acquisition process must be temporarily stopped when the buffer is completely filled so that the recorded data can be either stored on disk or analysed. Even if a second buffer is used, there is still a small gap caused by the time lost in running the control software to switch the buffers. Consequently, the finite buffer size, no matter how large, dictates the limit of the test duration if a continuous record of discharge activity is required. This problem can be solved with a circular buffer wherein data can be transferred into memory in a loop fashion. In other words, the memory location for storing data is incremented until it reaches the end of the buffer where it automatically reverts to the beginning. Thus once started, the acquisition process can be kept active indefinitely in the background without any further software intervention. The central processing unit (CPU) is free to concentrate solely on the task of processing and saving data in mass storage. As PD activity usually occurs over a small part of the alternating current cycle, the dynamic information rate is normally much higher than the average rate. By suitable choice of the memory buffer size, it can accommodate the sudden increase in PD numbers and the CPU will have enough time to process the data before it is over written with new data when a complete buffer cycle is reached. As a result, the CDA3 is able to operate as a virtual on line instrument which allows indefinite continuous recording and analysis with no loss of data, achieving a capability not available elsewhere.

A menu driven program controls the CDA3 operation and provides the user with different modes of analysing the recorded raw data. The integration period is software controlled, typically set to 10 seconds. Results
are displayed in tabular / graphical formats on a monitor which takes less than 2 seconds for a 33 MHz machine. The main mode plots the univariate distributions and also tabulates the integrated quantities and statistical moments. The second mode continuously plots the integrated quantities after each integration period so that one can see the changes in the discharge activity over a longer time scale. The third mode is the scatter plot which gives an estimate of the phase position and the amplitude of the discharge of each individual discharge pulse. With CDA3 analyser it is possible to get 32 statistical operators and 6 integrated quantities. The statistical operators, integrated quantities and univariate distributions available with CDA3 analyser are listed out in table 2.5.

Table 2.5
List of statistical operators, integrated quantities and univariate distributions available with CDA3 analyser

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<th>Distributions</th>
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<td>Peak discharge</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>Peak Discharge Vs Phase</td>
<td>Average discharge</td>
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<td>Skewness</td>
<td>PD Pulse Count Vs Phase</td>
<td>Average current</td>
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<td>Kurtosis</td>
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<td>Discharge power</td>
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<td>Quadratic rate</td>
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<td>PD Pulse count</td>
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2.11 VIRTUAL INSTRUMENTATION BASED PD ACQUISITION SYSTEM

2.11.1 General

This section describes a virtual real time partial discharge measuring system starting from capturing of PD pulses and applied test voltage, analyzing, displaying and controlling or monitoring of signals supported by Virtual instrumentation (VI). VI empowers users to build their own instrumentation systems with standard computers and cost effective hardware. Mixing and matching the choice of data acquisition and instrumentation control hardware, including all of the existing instruments to create virtual instrumentation that exactly meets all requirements is possible. The year 1996 marks a major milestone in virtual instrumentation (VI) software. These software centred systems leverage off the computational, display and connectivity of popular computers to give the power and flexibility to build each of instrumentation functions to meet all requirements. Graphical programming allows to quickly view test results and generate reports using simple menu choices with control. Hewlett Packard (HP) offers visual engineering environment (VEE). The visual programming language is utilised for the development of the real time data acquisition and control applications of partial discharges. The task of classification of PD patterns is dealt with the power of VI and VEE package. The HP VEE is one of premier graphical programming languages used during test and measurement in design industry. It provides virtual front panels for hundreds of instruments. It is ideally suited for the acquisition of complex PD current pulses of micro second or nano second duration. Typical graphical programs to acquire and display signals are depicted in figures 2.19 and 2.20.
Figure 2.19 Graphical programming to capture PD signals
Figure 2.20 Graphical programming to display the acquired signal
With graphical programming, productivity is dramatically increased compared to textual languages. Analysis and display of data is simple. Direct manipulation of visual objects (on-screen icons) leads to the solution quickly and intuitively. The data can be from a file, user input or mathematical generation. The visual elements for interface boards, serial and general purpose input/output (GPIO) bus are available. This feature helps the users to spend less time on input-output implementation (major hurdle faced by a programmer) in development environment and more time in getting results. Graphical programming resembles a data flow diagram, which is easy to maintain and understand. Gathering data from instruments, data analysis and creation of operator interfaces are made simple. VEE integrates with standard languages and can call existing textual languages or be called by them.

2.11.2 Program Development

A development software is designed exclusively for test engineering based on windows. It ensures an environment for developing real time data acquisition and control applications without programming, avoiding the burden of tedious line-by-line coding. Control of processes with data logging, display and multi tasking for industrial control applications is the most appreciated trait of this approach. In graphical programming, a general flow of execution through a program is called propagation. Propagation through a program is not determined by the geographic locations of the objects in the program, but rather by the way the objects are connected. Propagation is primarily determined by how the data input/output pins of the objects are connected. Order of execution can be altered by changing the sequence input/output pins. The sequence pins are used while controlling external devices such as instruments.
2.11.3 PD Data acquisition and preprocessing

As discussed previously, detection of PD is based on energy exchanges and PD measurements are qualitative. Origin of discharge is indicated by its discharge pattern and its variation with voltage and time. In order to make sure that diagnosis is true and correct, further study of the discharge is often necessary. A 12 bit, 20 Mega samples/second digitizer (1429B) containing 2 analog channels, memory, time base and data paths is ideally suited for capturing transient PD pulses and applied voltage (HPE 1421B 1996) and utilised in this thesis work. Of course, computerised discharge analysers are also used to capture and analyse the PD activity in this work. They are dedicated and are not cost effective. Analog channels have their own signal conditioning circuits and analog to digital converters. Separate paths are provided and thus the input gains and impedances can be matched to the incoming signals. Two modes of capturing the signals are available; differential mode offers a high impedance to minimize circuit loading, while the single-ended mode can be programmed for 50 or 75 Ohms to match source impedances. Synchronisation of PD pulse and applied voltage is done using arm and trigger signals generated internally or received from a variety of sources provided by different instruments. Duration of the PD data recordings is also programmable leading to easy analysis of phase resolved PD distributions. Valuable information about the defects could be explored with the display of results. Real time mathematical, statistical and logical processing of signals are possible. Modification of graphs and charts during data display makes the processing more meaningful and informative. Improvement of test system performance can easily be achieved with this development environment. VEE provides a tool to display signals in frequency domain and even mathematical formula to calculate and display the Fourier spectrum giving valuable information of any transient signal. A typical plot showing a signal and its Fourier spectrum is shown in figure 2.21. Also unambiguous recognition is
Figure 2.21 A typical plot showing a signal and its Fourier spectrum
possible for codifying the correlation existing between the defect and its distribution pattern applying suitable statistical approach. Different statistical approaches are provided by the VEE tool which simplify the task of classification of PD faults or defects.

2.12 SUMMARY

With the introduction of computer aided processing, the electrical insulation evaluation based on the PD inception voltage and the highest inception level has improved. Digital evaluation has greatly improved the recognition of discharge patterns and the correlation of these patterns with various types of defects. A powerful interpretation of the discharge signals is possible with the recording of a large number of discharge quantities measured simultaneously, making use of their stochastic nature. A computer aided discharge analyser is able to register continuous PD events and multi parameters. Digital techniques help to improve the sensitivity of the measurements by allowing the variation of noise threshold level depending on the background noise. When dealing with automation of PD measurements at least the element of recording of PD quantities should be given due care. To obtain the correct shape of the PD pulse, high sampling rates are required when recording PD pulses from a broad-band PD detector. The shape of the PD pulses at the input of the analog to digital convertor depends on the RLC network represented by the test object, the measuring impedance and the characteristic of the band pass filter of the PD detector. When a PD detector with a bandwidth of 40 to 400 kHz is used, a sampling rate of at least 5 MHz is required to digitise the PD peaks. The continuous recording of one minute PD test would require 300 MByte of memory. This is technically feasible but its cost makes it impractical. The sampling rate can be reduced by a factor of 2 to 4 when the shape of the PD pulse will be mathematically interpolated. However, to achieve a peak value accuracy of ±5% for different shapes of the PD pulses, such mathematical routines become very complicated. Accurate digital recording of the shape
of PD pulses makes sense for strictly defined test objects whose equivalent electrical circuit is known. Using detection circuits with bandwidths of some hundreds of megahertz up to a gigahertz, conclusions regarding the defect can be drawn from the shape of the PD pulse. Generally such ultra wide-band detection circuits are not easy to realise in an industrial environment. More over the pulse distortion in the path between defect and PD detector affects the information. To provide correct integration of a PD pulse as per the IEC 270 recommendation (the upper limit of the frequency range of a PD detector which should be less than 1/3 of the resonance frequency of the test object) systems with bandwidth less than 500 kHz is selected. A sampling frequency of minimum 200 kHz is found to be adequate to register the peak values of the PD pulses. To successfully record the PD pulses, sampling frequency of 500 kHz is fixed; in this way continuous recording of discharges is assured. Provision to switch between wide-band and narrow-band facilitates the interference noise to take a lesser value. The PD pulse resolution is found to be very good. It is found that the effect of 'wide band' and 'narrow band' PD measuring systems depends strongly on the duration of the PD current pulses. Capturing of more stochastic properties of PD and definition of new parameters helps to assist in the assessment of the quality and condition of insulation systems. In-depth analysis of PD functions is possible as the digital methods permit to store as much relevant information as possible. This feature also offers a decision-making aid for product development.