PARTIAL DISCHARGE MEASUREMENT

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PARTIAL DISCHARGE MEASUREMENT

Definition

Partial discharges are electrical discharges that do not completely bridge the electrodes are called partial discharges. They are localized to a small area within an insulating medium.

Concerns of Discharges

Besides creating light, audible noise, and ozone discharges (ozone is used to age rubber) can also:

- Generate ultra violet radiation. UV radiation can degrade certain fibers and polymers, such as polypropylene and polyethylene.
- Create nascent oxygen (another strong oxidizing agent as is ozone)
- Create nitric acid in the presence of moisture. (Another powerful oxidizing agent. Nitric acid reacts violently with many organic materials)
- Create oxalic acid (within polyethylene).
- Cause mechanical erosion of surfaces by ion bombardment.

Insulating Materials

FIG 2.1 is a drawing depicting an insulating medium. This insulating medium could be a solid or a liquid. A power supply, in this case an AC supply, is being used to apply a voltage across this insulating medium via two conductive plates. An **electrostatic field** is set up across the insulating medium and, thus, a voltage gradient is created.

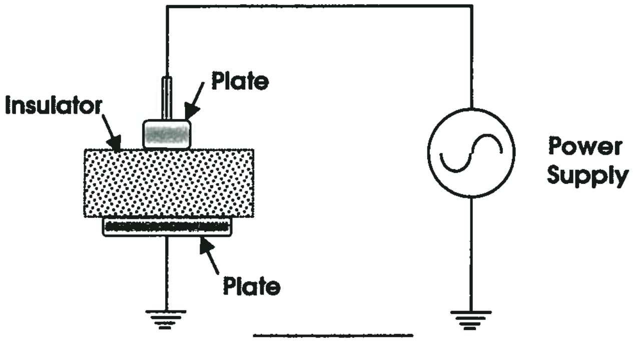


FIG. 2.1

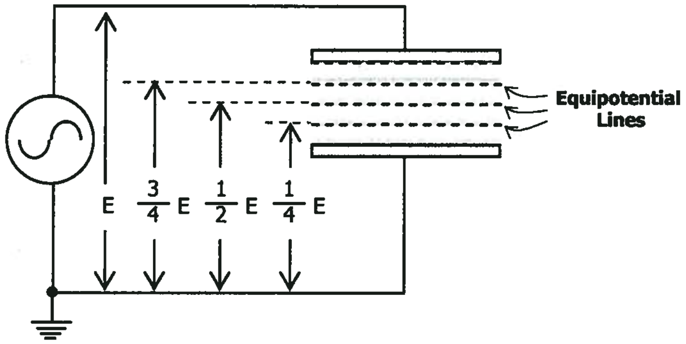


FIG. 2.2

In **FIG 2.1** it can be seen that the plates and insulating medium form a capacitor. In a homogeneous medium, the electrostatic field will cause the voltage to be distributed evenly across the dielectric material. In the drawing to the right, a capacitor is drawn with **equipotential lines** drawn showing this even distribution.

A similar occurrence can take place when dissimilar insulating mediums are involved. In **FIG 2.4** a capacitor with a homogeneous insulating medium is given. The electric field intensity across the entire insulating medium is consistent.

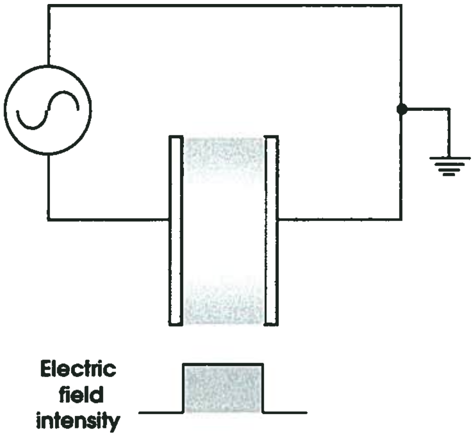


FIG. 2.4

Non-Homogeneous Materials

In **FIG 2.5** a capacitor with to dissimilar mediums is given. It can be seen that the electric field intensity (ϵ_1) is greater across D_1 than is the electric field intensity (ϵ_2) is across D_2. The electric field intensity (ϵ_1) being greater across D_1 means that the permittivity is less than that of the permittivity of D_2.

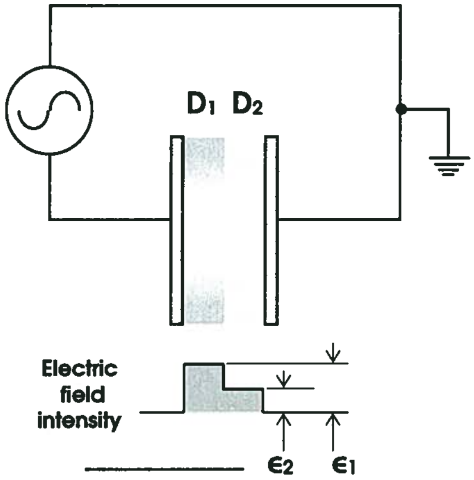


FIG. 2.5

Voids in Insulating Materials

What happens when the insulating medium contains a void? **FIG 2.3** is a drawing of such a condition.

The capacitance of:
- the complete insulation is represented by "**a**".
- the cavity is represented by "**b**".
- the dielectric is series with the cavity is represented by "**C**",

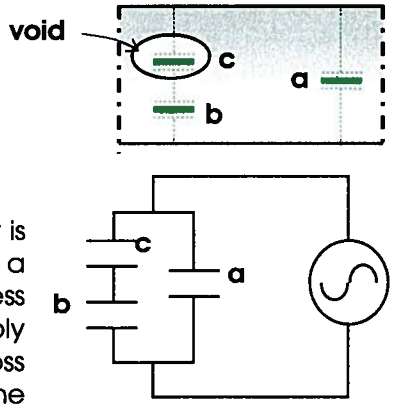


FIG. 2.3

In **FIG 2.3**, the void is filled with air. The **permittivity** of the air is much greater than that of the insulating medium. Having a greater permittivity, the air will also have greater voltage stress (electric field intensity) across it. When the power supply voltage is raised to a certain point, the voltage stress across the void ("c") will no longer hold. Being that it is within the insulating medium, only the localized area of the void ("c") will break down. This will not cause a breakdown of the overall insulating medium ("a").

Types of Discharges

In **FIG 2.6** various types of discharges are depicted. These types of discharges are referred to as partial discharges. These are internal to the insulating medium. These were described in very basic terms above

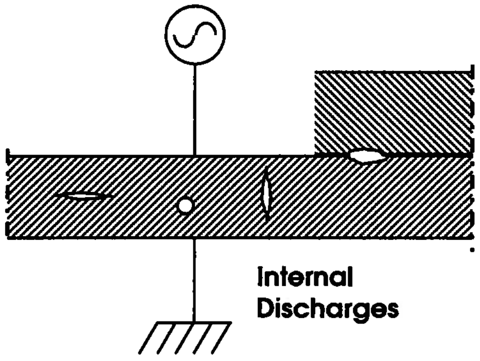


FIG. 2.6

The discharges in **FIG 2.7** and **FIG 2.8** are a bit different in that they are external to the insulating medium. This type of discharge, unlike internal discharges, can produce light, audible noise, and ozone. Even though they are sometimes referred to as partial discharges, they are most often referred to as corona.

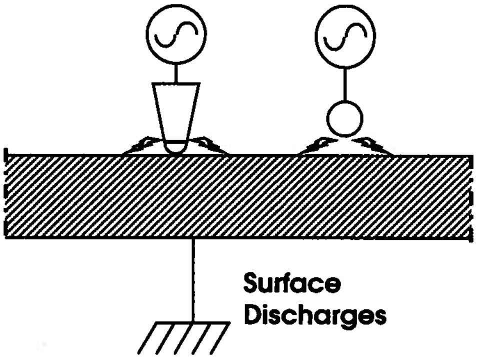


FIG. 2.7

The definitions of both types of phenomenon as given in ASTM D1868-D93 are:

Partial Discharge: An electrical discharge that only partially bridges the insulation between conductors. A transient gaseous ionization occurs in an insulation system if the voltage stress exceeds a critical value, and this ionization produces partial discharges.

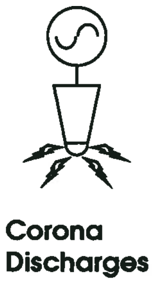


FIG. 2.8

Corona: A luminous discharge due to ionization of the air surrounding a conductor around which exists a voltage gradient exceeding a certain critical value.

Brush (Surface) Discharges

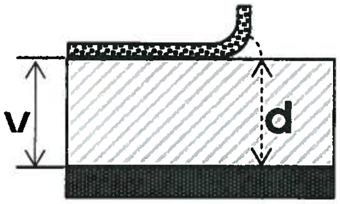


FIG. 2.9

When the onset voltage is exceeded, partial discharges occur which develop with increasing voltage from corona to brush discharges along the surface. The intensity of these gliding discharges and their onset voltage depend upon the magnitude of the surface capacitance. The larger it is, the larger the discharge current which flows from the tip of the brush discharge through the insulator as a displacement current. This leads to extension of the high voltage potential on the surface, without appreciable reduction occurring in the field strength at the tip of the discharge, further growth of the discharge is thus favored.

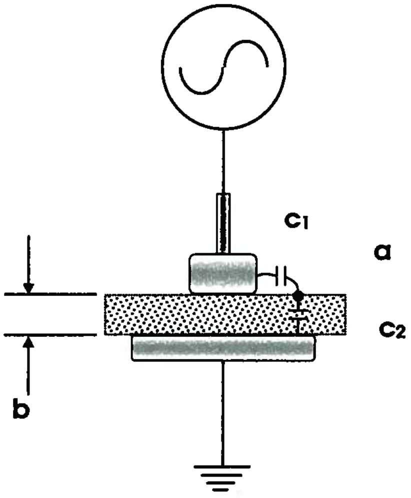


FIG. 2.10

Internal Discharges (Voids)

FIG. 2.11 is a representation of a void in an insulating medium. Each of the "plates" corresponds to the walls of the void in the presence of an electrostatic field as set up by the power source. The negatively charged electron is attracted to the left by the positive charge on the "+" plate and also repelled by the negative charge of the "-"plate. If the electron is not held in place it will travel to the positive plate. The energy necessary to do this is supplied by the power supply. The potential difference between the "+" terminal and the "-"terminal can be thought of as the mechanical work necessary to move the electron that distance.

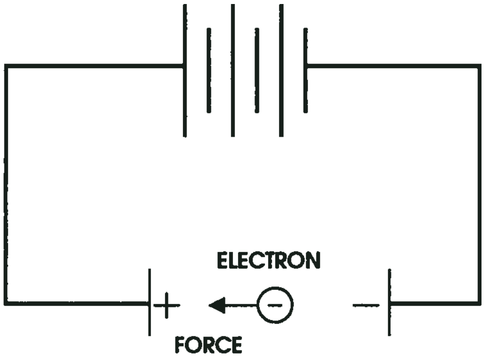


FIG. 2.11

The distance between the two plates is an example of a **potential gradient**. The definition of a potential gradient is the voltage divided by the distance.

FIG. 2.12 shows an atom in an electrostatic field. The negatively charged electron is subjected to a mechanical force to the left and the positively charged nucleus is subjected to a mechanical force to the right. These forces distort the atom's structure so that the nucleus is to the right of center of the electron's path. If the power supply is adjusted to give a higher and higher potential difference, a point will be reached when the external mechanical forces exerted on the electron and nucleus will overcome the internal forces and the outer electron will be pulled out of the atom. The atom is then said to be **ionized**.

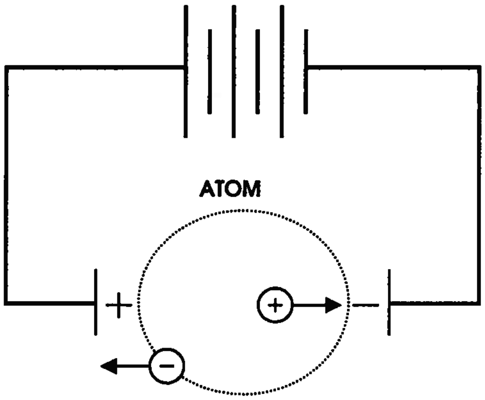


FIG. 2.12

The electron with its light mass will quickly travel to the positive plate and enter the terminal. The positive ion, or nucleus, being heavier (50,000 times as much in the case of air!) will travel more slowly to the negative plate. Upon reaching the negative plate it receives an electron to replace the one it had lost. It once again becomes neutral. When the electron combines with the nucleus, it admits a quantum of light or radiant energy which may of may not be visible.

The mechanical energy needed to pull the electron out of the atom comes from the electrical energy supplied by the voltage source. The atom, in having the electron pulled away from the nucleus, receives stored potential or mechanical energy. When the electron falls back onto the atom, this potential energy must be given up and it appears as radiant energy. The ultimate source of the radiant energy is, of course, the generator.

Due to the potential gradient, or force on the electron, a free electron moving in a gas undergoes acceleration. If it has picked up enough speed (kinetic energy) by the time it collides with another atom, it can knock out an electron from that atom leaving it also ionized. Both of these atoms are able to travel on to do the same. This can continue on until a full breakdown occurs. This process is referred to as electron avalanche.

The movement of electrons to and into the positive plate and movement of positive ions to the negative plate mean a flow of electrons from the positive plate, through the power source, on to the negative plate. This transfer of electrons provides the energy to maintain the discharge. Since the electron is such a small charge, it is measured in **coulombs**. One coulomb per second is equal to one ampere. One coulomb is equal to 6.28×10^{18} electrons.

External Discharge (Corona)

In air there are free electrons due to natural processes such as cosmic rays. Having a negative charge, these electrons are affected by the electrostatic field surrounding a conductor.

As the voltage sine wave increases in a positive direction, the electrons are attracted toward the conductor. The speed at which the electron travels towards the conductor is dependent upon the intensity of the electrostatic field. If the field is weak, the electrons will bounce off of an oxygen or nitrogen molecule in its path.

However, as the field strengthens, the electron will collide with a molecule at a higher rate of speed. If the field continues to strengthen, the electron will reach a speed at which it will hit a molecule hard enough to knock an electron from the molecule's outer shell.

Once free, this electron will also make its way toward the conductor. Both electrons will eventually strike another molecule, releasing two more electrons. This is the same electron avalanche process as described above.

The molecule, by losing an electron, becomes "**ionized**" and, therefore, carries a positive charge. It begins its journey toward the negative electrode. Occasionally a free electron comes into contact with and is captured by an ionized molecule. When this happens a quantum of energy is released in the form of an electro-magnetic wave. When this energy is released in the presence of an oxygen or nitrogen molecule, light is emitted.

Various Observations of discharges

First Observation

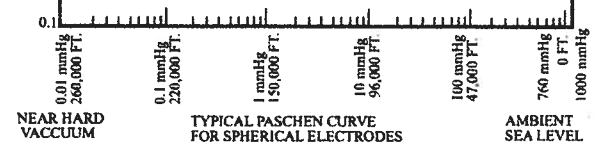
Referring to both corona and to partial discharge, a very interesting phenomenon occurs as voltage is increased.

> As the voltage cycle raise in the positive direction, the free electrons near the conductor surface begin to move toward the conductor. Many do not gain enough speed during this comparatively short trip to knock electrons free from molecules, so there is not much opportunity for ionization to take place.
>
> As the voltage increases in the negative direction, the free electrons near the conductor surface begin to move away from the conductor. These electrons have more room to travel and have the opportunity to pick up greater speed. Of course, at this greater speed, they will knock more electrons out of molecules, creating much greater ionization.

Thus, if you could see the corona with reference to the wave shape, you would find that the discharges appear much more frequently on the negative half cycle. (We actually can see these discharges with a pd detector, as we will find out later).

Second Observation

In 1899, a German scientist named F. Pashen published a paper which set out what has become known as Paschen's Curve. He spaced two spherical electrodes at 1cm. He then reduced the ambient pressure in increments from sea level. This chart is to the right. At sea level, about 30kVDC is required to initiate an arc across the electrode gap. At 47,000 feet the arc level drops to about 1200 VDC. The worst altitude is 150,000 feet, where only about 300 VDC will arc across the electrodes.



TYPICAL PASCHEN CURVE FOR SPHERICAL ELECTRODES SPACED AT 1 CM (.393 INCHES)

FIG. 2.13

What does this have to do with discharges? From FIG 2.11 you can see that as the pressure (air in this case) changes, the breakdown level is not linear. As the pressure decreases the voltage at which a gap will break decreases. However, as the gap nears a vacuum, the voltage breakdown begins to increase once again.

Third Observation

When the discharges begin this flow of electrons is a current flow When a current is flowing, a magnetic field is set up. These magnetic waves can induce pulses in nearby antennas. This is why corona effects radio reception, and why partial discharge detectors can pick up radio station transmissions.

Fourth Observation

The breakdown path is limited by a thing called space charges. These charges disappear quickly within milliseconds and determine the repetition rate of the corona discharges.

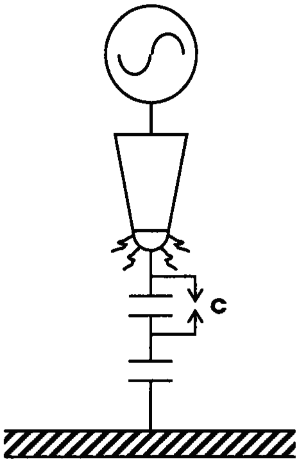


FIG. 2.14

If a positive ion appears in the vicinity of the point it is attracted by the electric field and moves toward the point. The ion hits the electrode and releases one or more electrons which, by repetition, cause a cloud of positive ions near the point and negative electrons which travel away from the point. The electrons slow down at a greater distance from the point and attach themselves to the oxygen molecules in the air. Two regions with space charges now have been formed. A positive space charge has built up in the nearest vicinity of the point by the slow positive ions.

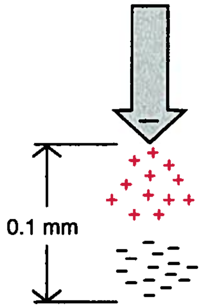


FIG. 2.15

At a greater distance, the negative ions, which are formed by adhesion of the electrons to the oxygen, cause negative space charges. The whole process takes place within a distance of 0.1 mm from the point and in a time interval of the order of 10^{-8} seconds. The space charge is shown in the drawing to the right. The negative space charge shields the electric field from the point, the positive ions move into the point without producing further ionization as the field strength is too low, and the discharge extinguishes. The negative space charge then moves away to the anode, the electric stress rises, and the next discharge starts.

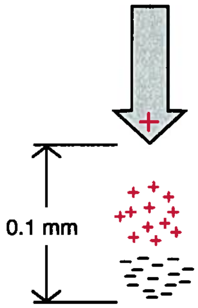


FIG. 2.16

If the point is positive, as in the drawing to the right, electron avalanches cause a distribution of space charges as shown. The electrons disappear at a greater speed and the slower positive ions shield the point from the electric field. The corona discharge stops until the positive ions have drifted away, and a new discharge starts. This is also recurrent.

Magnitude of Discharges

Apparent Charge

The actual charge that occurs due to a pd event is not directly measurable. Apparent charge is used instead. The apparent charge (q) of a pd event is not the actual amount of charge changing at the pd site. Instead, it is the change in charge that, if injected between the terminals of the device under test, would change the voltage across the terminals by an amount equivalent to the pd event.

Magnitude of the discharge (q) increases with the size of the cavity. However, the discharge magnitude of a cavity decreases with the insulation thickness.

The quantity of charge is normally given in coulombs. Partial discharge detectors typically give a direct reading in pico-coulombs. Earlier we stated that one coulomb per second is equal to one ampere. One coulomb is equal to 6.28 x 10^{18} electrons. A "pico" being equal to 1 x 10^{-12}, this means that when we talk about 1 pico-coulomb (pC) of discharge we are talking about measuring 6,280,000 electrons per second, which is a very small quantity of electrons.

System for Measuring Discharges

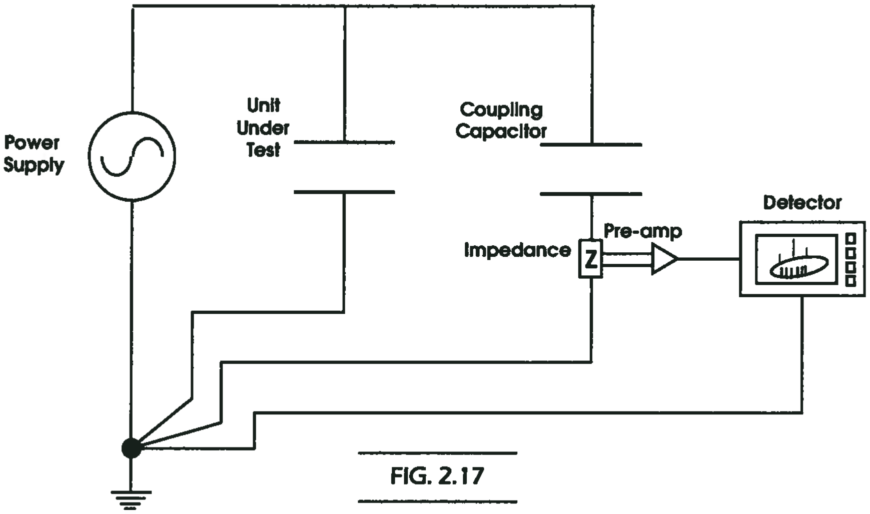


FIG. 2.17

FIG. 2.17 Shows a simplified diagram of a typical High Voltage System and Partial Discharge Detector used for measuring partial discharge.

The elements of the system are:

1. Power Supply
2. Coupling Capacitor
3. UUT (Unit Under Test)
4. Impedance and Pre-amp
5. Detector
6. Partial discharge free connections

The power being supplied to the measurement circuit must contain lower levels of discharge than what is to be measured. For instance, power cables typically must be less than 5pC. When power sources are specified for this application they are normally required to have less than 2pC at some specified level. This can be accomplished by either providing a test transformer that has less than 2pC at this same specified level, or by filtering the output of the test transformer.

> There are sources of disturbances other than the test transformer. The incoming lines to the test transformer can contain disturbances that can be mistakenly identified as discharges on the detector. The high voltage filter can reduce the levels of this disturbance. A shielded isolation transformer works well to greatly reduce line disturbances.
>
> Another source of disturbances, one which is much more difficult and costly to resolve, is air-borne in nature. Previously we found that corona can create audible noise on a radio. Being in the same frequency band, radio transmission can be measured on the partial discharge detector along with many other disturbances such as welders, solid-state circuits, and even lighting fixtures. The best solution to this is to place the Unit Under Test and the coupling capacitor inside of a faraday cage.

Grounding can also present a problem in measuring partial discharges in the form of circulating currents. Single-point earthing (as shown in **FIG.2.17**) may reduce or even eliminate this problem. If this does not cure the problem it may be necessary to isolate the test floor ground from the conventional ground.

Induced discharges can be another problem. This is caused by any components in the area that are either not grounded, or are poorly grounded. Even small pieces of debris on the surrounding floor can be the source of unwanted disturbances.

Bad contacts, loose connections, or poor grounding may cause disturbances readable on the discharge detector. These normally appear at the zero crossover points.

The coupling capacitor must be rated for the voltage and free of partial discharges.
The connections must be corona-free at the test voltage. The can be accomplished by sufficiently sized interconnects and toroids which are free of any sharp points.

Detection of partial discharges

FIG. 2.18 indicates the coupling capacitor **C_1** and impedance at the base of the coupling capacitor. These impedance units are normally referred to as quadrapoles. At one time they were known as power separation filters of which more appropriately describes their function. A very basic Impedance circuit is drawn consisting of an inductor **L_1** and a capacitor **C_2**. As the power frequency enters the impedance it has no trouble in passing through **L_1** and on to ground. The high frequency component, being partial discharge will not pass through the inductor as easily. It, instead, passes with no difficulty through **C_2** and on to the detector. In actuality the circuit is more complicated than this, and, there is an amplifier circuit at close proximity to the impedance.

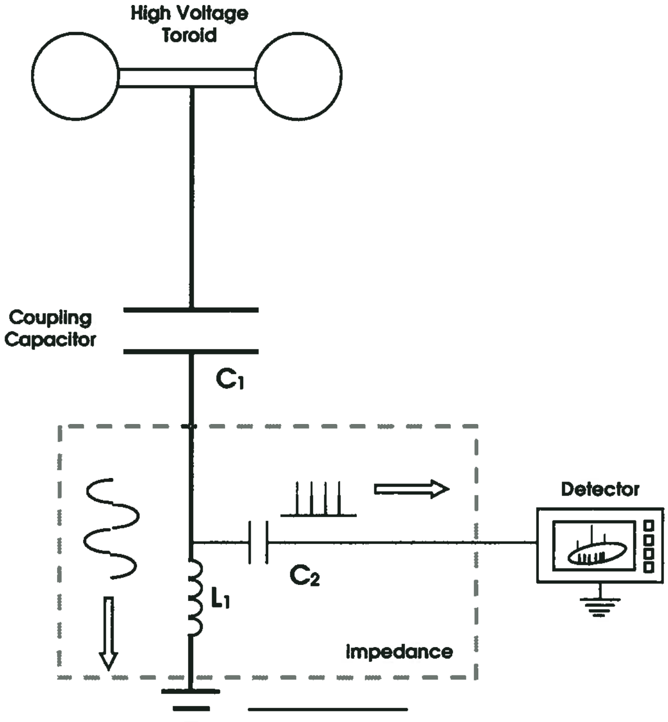


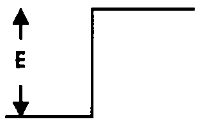
FIG. 2.18

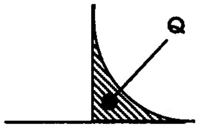
Calibration of Setup

Some type of a calibration device is needed to check the calibration of the "setup". As the Units Under Test change so may the calibration. One specimen may have a different capacitive value than the next one, which can affect the calibration. There are two main types of calibrators;

- On-line
- Off-line (hand-held)

Both perform the same task of injecting a known quantity pulse on to the setup as shown in **FIG. 2.19**, and setting the adjustment on the detector to read the same value as the known value pulse. The on-line type of calibrator is able to inject a signal at the same time as the high voltage is applied to the test sample. The advantage of this is that it is very convenient to calibrate (as well as recalibrate to a different value) with high voltage on without ever leaving the control console. The disadvantage is that it is much more expensive, and adds another potential source of discharge in the high voltage circuit. The off-line calibrator is relatively inexpensive. However, the set must be turned off to recalibrate. Most of the time in is more convenient to have two persons to perform calibration of "setup".





A very simple calibrator can be in the form of a square wave generator and a capacitor. Q = E x C

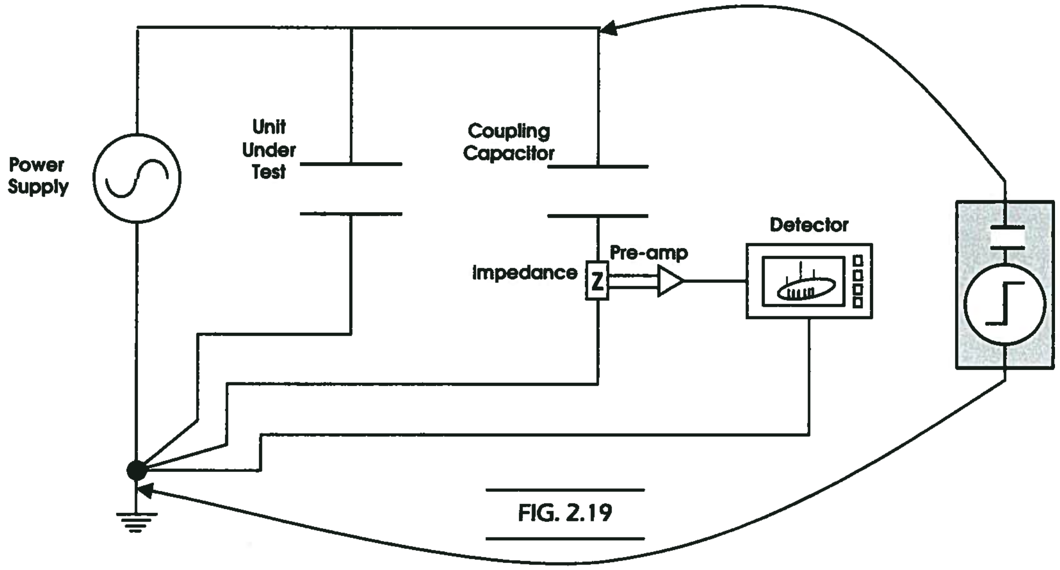


FIG. 2.19

Display of Partial Discharge Detector

The partial discharge detector will display the partial discharges in a phase-resolved manner, meaning that the discharges will appear at the same position on the wave shape as they do on the sinusoid.

FIG2.20 and **FIG 2.21** are both typical phase-resolved displays of partial discharge.

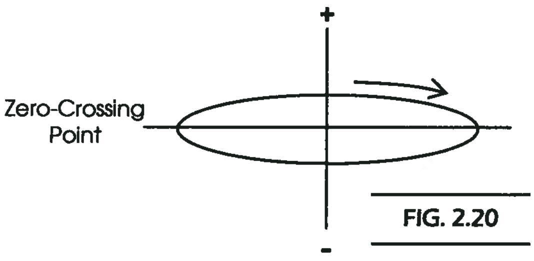


FIG. 2.20

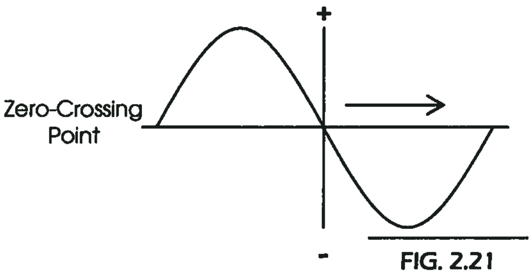


FIG. 2.21

In a typical occurrence of partial discharge, if the AC voltage is slowly increased, corona discharges occur at the negative half-cycle of the sine wave only. At first one discharge is seen. As the voltage is increased, other discharges begin to appear.

FIG. 2.22

At higher levels, impulses also appear at the positive half cycle. These impulses are usually more irregular and are of larger size.

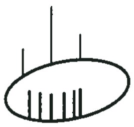


FIG. 2.23

Display of Partial Discharges On Detector

The high voltage across the dielectric is V_a, the voltage across the cavity, V_c, when voltage V_c reaches breakdown voltage U^+, a discharge occurs in the cavity (given by the paschen curve). The voltage then drops to V+ where the discharge extinguishes. This voltage drop takes place in less than 10^{-7} seconds, an extremely short period of time compared to the 60 millisecond duration of a sine wave. After the voltage has extinguished, the voltage over the cavity increases again.

The discharges in the cavity cause current impulses in the leads of the sample. Note that these impulses are concentrated in regions where the voltage applied to the sample increases or decreases most, therefore, at the crossover points.

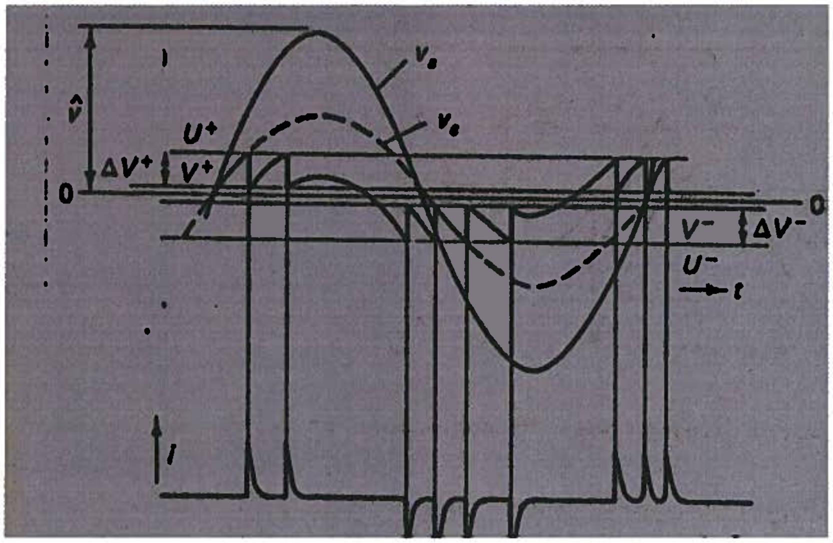


FIG. 2.22

Typically, if the voltage drops in both half-cycles are equal ($\Delta V^+ = \Delta V^-$) the impulses will give a stationary picture on a 60 cycle time base. If they are not equal ($\Delta V^+ \neq \Delta V^-$), the impulses move around the time base.

The voltage across the sample at which discharges start to occur when the voltage is increased is called **inception voltage**.

If the voltage is decreased after discharges have been started, the voltage at which the discharges extinguish is usually lower than the inception voltage. This is called the **extinction voltage**.

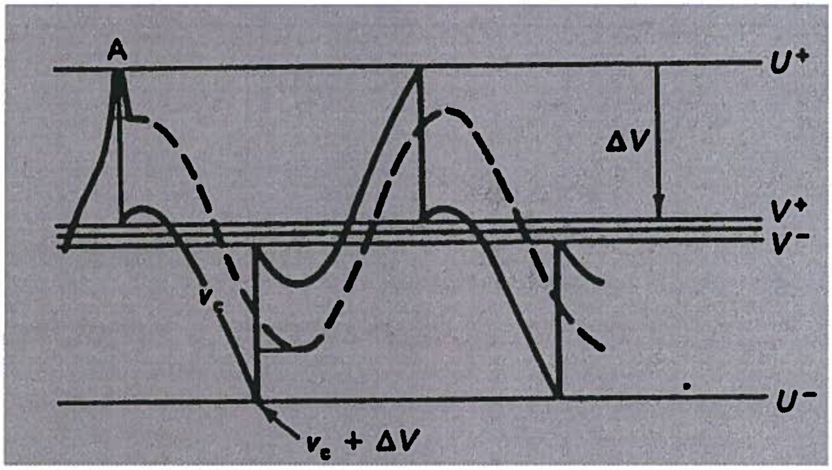


FIG. 2.23

Once a discharge has started, it can persist at a lower voltage than the inception voltage. In the figure above it is assumed that the first discharge starts due to a short over-voltage at "A". The voltage V_C over the cavity (originally smaller than the ignition voltage U^+ or U^-) reaches the ignition voltage at the other half-cycle owing to the surface charges which are left after the preceding discharge. Now the voltage V_C and the residual charge in the cavity co-operate and the discharge can persist at almost half the inception voltage. The extinction voltage typically is found to be in the 10% to 30% lower than the inception voltage. This is why some tests require that the sample be stressed at a higher voltage prior to pd testing at the rated voltage.

Discharges may become intermittent if the cavity is asymmetrical, with a breakdown voltage U+ being unequal to U-. The voltage over the cavity VC reaches reaches the breakdown voltage U+ at point "A", which results in a discharge. The surface charge and the voltage VC cause the void to break down again at B. The next discharge occurs at "C", earlier in the cycle than "A". The voltage in the next half-cycle passes through its minimum without reaching the value U-, so that no discharge can occur. The surface charge persists during many cycles and no more discharges occur until this charge has leaked away. Another sequence then starts and extinguishes again so that an intermittent discharge is observed. At a higher voltage the discharges become constant.

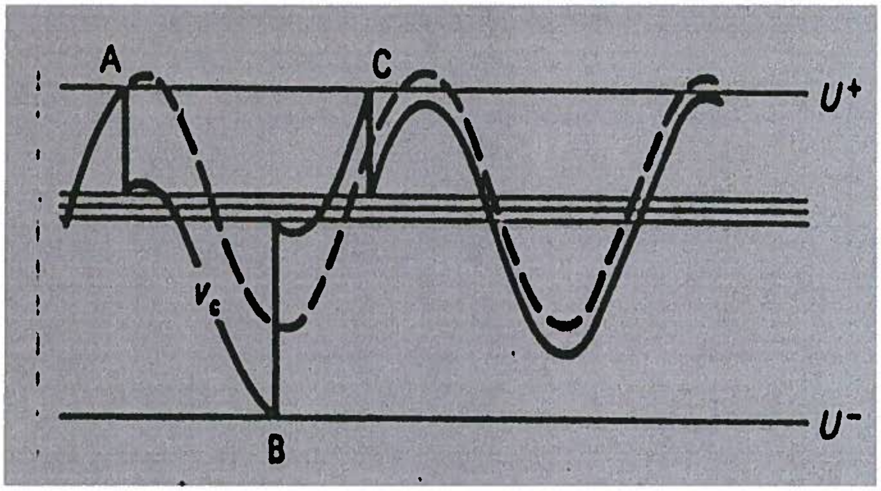


FIG. 2.24

When there is discharge it can often be diagnosed by several parameters:

- The location of the discharge(s) with relation to the phase.
- The discharge pattern.
    - Do the pulses grow or instantly appear?
    - Are the pulses on the rising side of the waveform?
    - Are the pulses on both the rising and decreasing sides of the waveform?
    - Are the pulses both on the positive and negative sides of the waveform?
- The steadiness of the pulse(s).
    - Are the pulses random or steady?
    - Are the pulses stationary or moving?
- The comparison of the inception and the extinction levels.
    - Does the pulse come in and go out at the same voltage level?