● Internal partial discharges

✔ Unwanted microscopic blasters or cavities can form in an insulating (ie. a PEX power cable) media during the manufacturing.

✘ Such cavities are to be found in the practical dielectric, which ideally should be homogeneous. For PEX (polyethylene) this can be caused by unsufficient degassing and/or wrong extruding.

✖ cracks and splits can form in boundaries between two different parts of a HV equipment, for instance between the metallic conductor and the insulation of a power cable.

✚ Every cavity will posess a significantly higher E-field strength than the surrounding, homogeneous dielectric. This is mainly due to the following two reasons:

1. Difference in permittivity of the (normally) gas filled cavity and the surrounding dielectric.

2. The geometry of the cavity

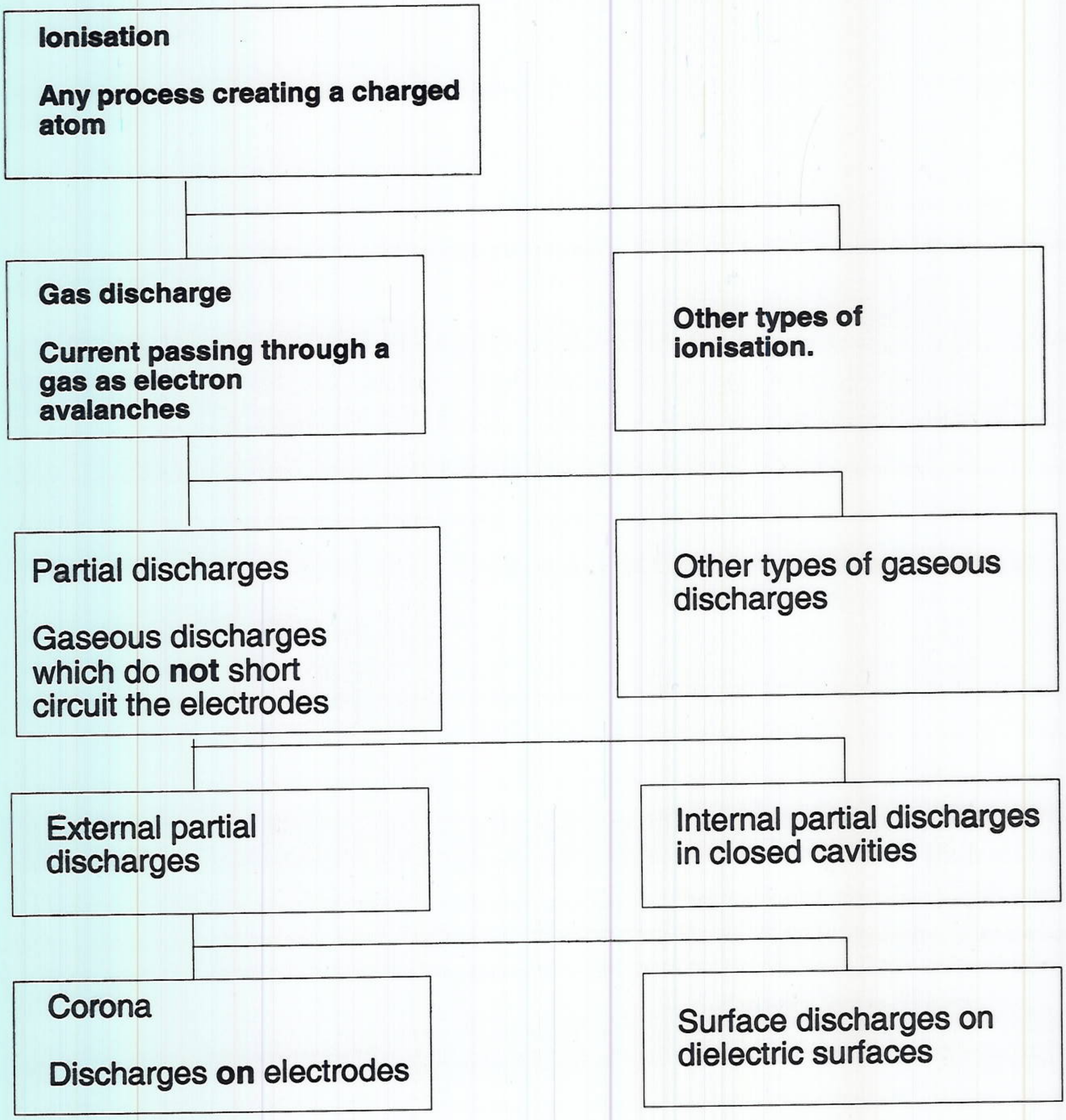
Exceeding the breakdown voltage U_d of the gas in the cavity will create a breakdown of the cavity.

✤ The breakdown(s) gives rise to very fast current pulses (ns) which outbalances the field of the cavity by means charge carrier movement from anode to cathode.

★ The E-field will be restored when the broken down and extinguished cavity capacitance recharges. A new breakdown happens as long as the voltage across the cavity $\hat{U} > U_{d,cavity}$. Repeated current pulses occur.

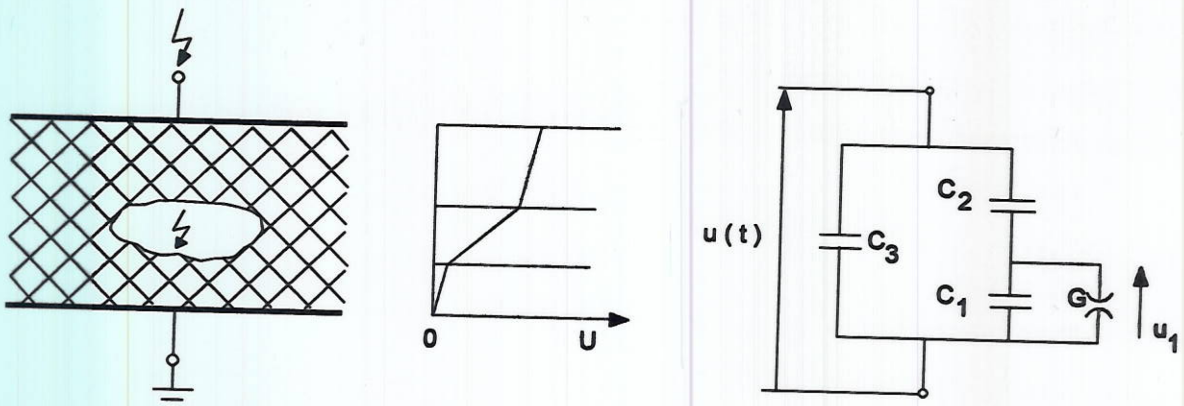
● Partial Discharges

Partial discharges can be subdivided into two cathegories; **External** partial discharges or **internal** partial discharges.



Internal partial discharges will in the long terms destroy the dielectric and thereby initiate a complete breakdown.

- **Example of a dielectric containing cavities with internal partial discharges**



EUT with cavities | Voltage distribution | Equivalent scheme

Fig. 9.10 Principles of internal partial discharges

- The capacitance C_1 is modelling the capacitance of the cavity, which will be discharged completely after the breakdown caused by exceeding the ignition voltage of the spark gap G.

- C_2 is the "healthy" series capacitance on both sides of the cavity.

- C_3 is the parallel capacitance of the dielectric around the "sick" branch.

- The relation (ratio) between the capacitances is always $C_3 >> C_2 >> C_1$.
1 2,

- Assuming an applied sinusoidal voltage gives the following voltage across the discharge cavity during "no-breakdown" ie. below the ignition voltage.

NOT BROKEN DOWN VOLTAGE

$$u_{10} = \frac{C_2}{C_1+C_2}\,u(t) = \frac{C_2}{C_1+C_2}\,\hat{U}\sin\omega t \qquad [V]$$

- Increasing the applied voltage to a maximum value of $\hat{U}_{ut}$ makes the voltage across the cavity equal to U_t ➔

$$\hat{U}_{ut} = \frac{C_1+C_2}{C_2}\,U_t \qquad [V]$$

SPARK IN CAVITY ⇒
$U_{10} = U_t$ ⇒
$U_t = \frac{C_2}{C_1+C_2}\cdot\hat{U}_{ut}$ ⇒
$\hat{U}_{ut} = \frac{C_1+C_2}{C_2}\cdot U_t$

- Applied voltages higher than $\hat{U}_{ut}$ gives a waveform with repeated discharges of the cavity.

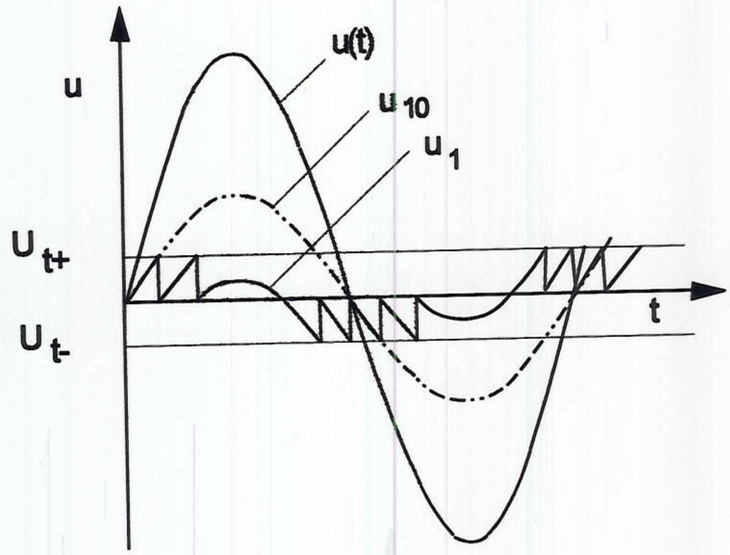


Fig. 9.11 Voltage waveform for internal partial discharges.

- A very important distinction between external and internal PD is the phase localization of the discharge activity. INTERNAL PD TAKES PLACE AROUND THE ZERO CROSSING OF THE APPLIED VOLTAGE !!

fordi spændingen falder U_t over både C_1+C_2

- The outbalanced charge per discharge must be equal to (remember $\hat{U}_{ut} = (C_1 + C_2)/C_2 \bullet U_t$ and $Q = C \bullet U$):

$$Q_1 = (C_1 + C_2)\, U_t$$

- The PD discharge amount Q_1 cannot be determined without knowing the fictouos partial capacitances C_1 and C_2.

- At the instant of discharge (ignition of G) the voltage will drop across C_2 (healthy part of branch) with the voltage drop:

$$\Delta U_{C1} = \Delta Q_{C1}/C_1 = U_t$$

- The voltage across the branch C_1 - C_2 is U_t lower than across C_3 (the rest). This voltage difference recharges C_2 the amount $\Delta U = U_t$ to the level of the applied voltage. The recharge current path is through the ignited spark gap G. C_2 will be supplied with the "apparent"charge Q_{1t}

$$Q_{1t} = C_2\, U_t \neq Q_1$$

which differs from the charge Q_1 outbalanced in the PD cavity.

- The charge Q_{1t} can be measured in the external circuit by means of:

  - Voltage drop

  - Outbalancing current

● **Detection of of partial discharges**

Partial discharge activity can be detected in several ways, which all have their origin in the outbalancing of the small amounts of energy during the PD.

1. Electrical outbalancing currents

2. Dielectric losses

3. Electromagnetic radiation (ligth)

4. Audiovisual (sound)

5. Increased gas pressure

6. Chemical reactions

The oldest method is the "hissing" test. It is only useful for detecting external partial discharges and demands a very good hearing performance.

It can be very difficult to distinguish between PD from the EUT or the setup.

● Measurements for detecting partial discharges

★ Measurement of voltage drop ΔU

PD activity in cavities will give rise to outbalancing charges in the complete system. This is due to the periodic elimination of the charge of the PD cavity - this charge is absorbed by the voltage source.

Comparing the charge of the EUT **before** and **after** a PD has taken place makes it possible to determine the voltage drop across the connecting terminals to:

$$\Delta U_{EUT} = \frac{C_2}{C_3 + C_2} \bullet \Delta U_{cavity}$$

Hereby is seen that measurable voltage drop at the connecting terminals is proportional to voltage drop of the cavity.

- The proportionality constant is the ratio of the "sick" branch healthy capacitance C_2 to the capacitance C_3 of the EUT, $C_2 <<< C_3$!!!

- $\Delta U_{cavity} = U_t$ is VERY small compared to the applied voltage !!

The ratio of the voltage drop ΔU_{EUT} and the applied voltage is in terms of measuring metods, **very** unfavourable:

Real life practical applications yields:

- $\Delta U_{cavity} = 0{,}1 - 10$ kV

- $\Delta U_{EUT} = 0{,}1 - 1$ V

- $U_{N,\,EUT} = 100 - 1000$ kV

✱ Apparent charge method

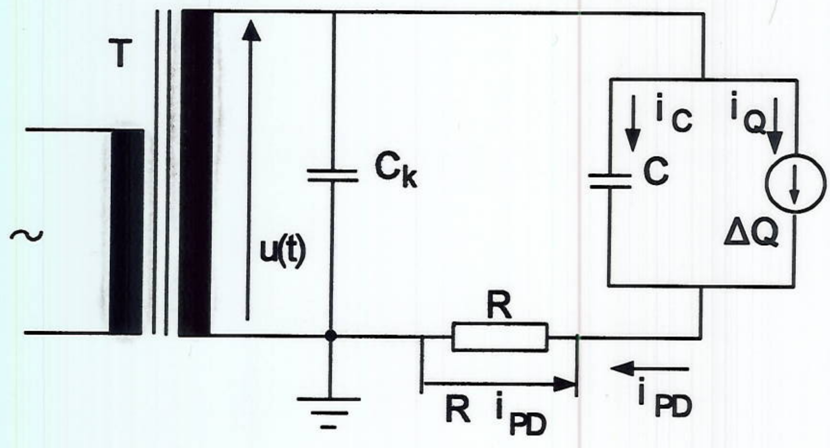


Fig. 9.12 Circuit for measurement of partial discharges
C EUT with PD, T Transformer,
R Measuring resistor, C_k Coupling capacitor

- The current source delivers a very short (in time) current pulse with the charge ΔQ.

- Assuming a suitable impedance (inductive) of the circuit from the HV transformer to the coupling capacitor C_k makes the current pulse flow in the loop consisting of C_k and the EUT.

- The coupling capacitor C_K is a storage capacitor which aims to outbalance the voltage drop when the cavity breaks down. This is accomplished by means of a charging current i(t), which is flowing between C_K and the EUT. Making $C_K >> C_1$ will give rise to a complete restoration of the voltage drop and the "used" charge will be equal to the sum of current i(t) in time passing during the voltage restoration.

For a single very short ($\Delta t = 0$) current pulse the following apply:

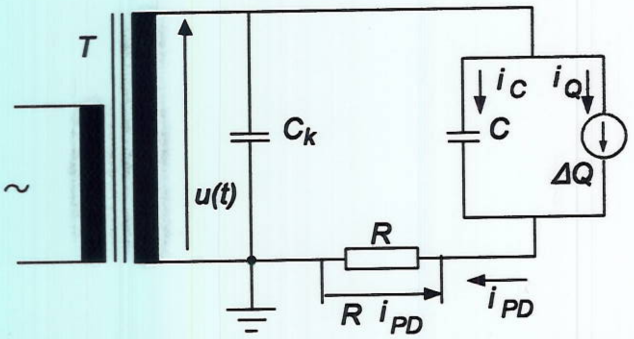
$$\Delta Q = \int_{\Delta t \to 0} i_Q \, dt = \int_{0-}^{\infty} i_Q \, dt = constant$$

DIRAC
UNIT PULSE
KREYSZIG pp. 266

This suddenly changes the voltage across the EUT:

$$\Delta U = \frac{\Delta Q}{C} \quad [V]$$

From the equivalent scheme it is seen that:



$$i_{PD} = i_C + i_Q \quad \Rightarrow$$
$$i_C = i_{PD} - i_Q$$

Eliminating i_C yields the current pulse of the source with charge $\Delta Q = U \bullet C$:

$$i_{PD} R + \frac{1}{C_k} \int_0^t i_{PD} \, dt + \frac{1}{C} \int_0^t i_C \, dt = 0$$

$$i_{PD} R + \frac{1}{C_K} \int_0^t i_{PD} \, dt + \frac{1}{C} \int_0^t i_{PD} \, dt - \frac{1}{C} \int_0^t i_Q \, dt = 0$$

$$\int_0^t i_Q\,dt = \Delta Q = (1 + \frac{C}{C_k}) \int_0^t i_{PD}\,dt + i_{PD}\,R\,C$$

This assumes that the current pulse is represented by Dirac's unity pulse.

Dirac's unity pulse has the mathematical characteristics of an infinetely short duration in time and the area = 1. DEFINITION

KREYSZIG
DEFINITION PP. 266

$$\delta(t-a) = \begin{Bmatrix} \infty & for\ t = a \\ 0 & for\ alle\ andre\ t \end{Bmatrix} \quad og \quad \int_0^\infty \delta(t-a)\,dt = 1$$

This makes it possible to treat the charge $\Delta Q = \int i_Q\,dt$ as constant.

The interpretation of the loop equation is thereby:

- At the instant of the current pulse (PD in the cavity) i_{PD} infinetely fast approaches a finite value. At time instant t=0 the integral=0 and the initial value of i_{PD} can be calculated to:

$\int_0^t i_{PD}\,dt$

$$\Delta Q = i_{PD}\,R\,C = \Delta U_{PD}\,C$$

- For t ➜ ∞ makes i_{PD} ➜ 0 and the factor i_{PD}•R•C disappears, giving:

$$\Delta Q = \left(1 + \frac{C}{C_k}\right) \int_0^{t\to\infty} i_{PD}\,dt = \left(1 + \frac{C}{C_k}\right) \Delta Q_{PD}$$

The following can be seen from the last 2 equations:

-It is possible to determine ΔQ on the basis of the capacitance C of the EUT and the voltage drop ΔU_{PD} and calculate ΔQ (ΔQ is the physical PD IN the cavity - not the measured one). The voltage drop ΔU_{PD} is very difficult to measure as the ratio $\Delta U_{PD}/U_{applied} << 10^{-3}$.

- It is possible to measure the current through R and integrate with respect to time yielding ΔQ_{PD}. The "real" partial discharge ΔQ can be calculated on the basis of the capacitance C of the EUT and the capacitance C_K of the coupling capacitor as:

$$\Delta Q = \left(1 + \frac{C}{C_K}\right) \bullet \Delta Q_{PD} \qquad [pC]$$

- Having $C_K >> C$ makes $\Delta Q = \Delta Q_{PD}$. This is not always the case in real life and the ratio $(1 + C/C_K)$ is very decisive to the measuring accuracy.

- Both ΔU_{PD} and ΔQ_{PD} is statistical functions and should be averaged and aftertreated according to standards (IEC 270) to get comparable and reproducable measurements.

PD measurements very often only yields information on maximum size discharge [pC]. One thing is certain:

- The deterioration and thereby the lifetime is affected of ***all*** partial discharges.

This has given rise to the development of socalled **PD-analyzers** which do not only measure maximum value [pC] but all discharge pulses.

- Number of pulses, pulse interval and the amplitude of every single pulse.

Such apparatus are very sophisticated and has a need for powerful computing tools to take hand on the large amount of data.

Recent research is pointing at the fact that this improved knowledge of the PD phenomena will give better possibilities of lifetime estimations.

✿ Other rated values for partial discharges

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Average discharge current I

$$I = \frac{1}{T}\left|q_1 + q_2 + ... + q_m\right| = \frac{1}{T}\sum_{i=1}^{m}\left|q_i\right|$$

Quadratic rate D

$$D = \frac{1}{T}\left|q_1^2 + q_2^2 + ... + q_m^2\right| = \frac{1}{T}\sum_{i=1}^{m}\left|q_m^2\right|$$

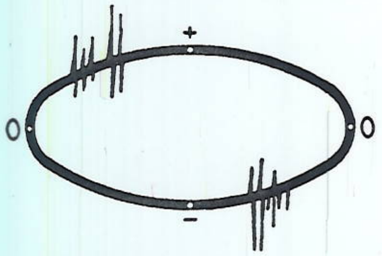
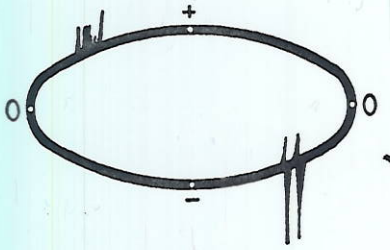
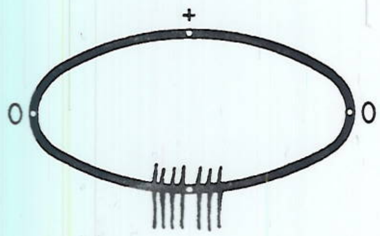
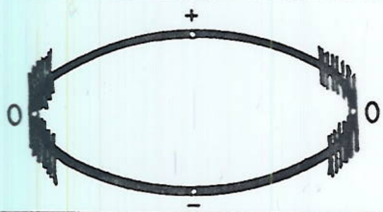
DIRECTLY RELATED TO INSOLATION DECOMPOSITION

Discharge power P

$$P = \frac{1}{T}\left|q_1 \bullet \mu_1 + q_2 \bullet \mu_2 + ... q_m \bullet \mu_m\right|$$

q_i is the individual partial discharges and μ_i the instantaneous value of the voltage at the instant of q_i.

TABLE 5.1

Discharge pattern	*Characteristics*	*Origin*
 (a)	Fairly symmetric pattern, stationary or/and wandering impulses	This is the usual picture of internal discharges in voids and in impregnated dielectrics
 (b)	A few large discharges in the positive half-cycle, several smaller discharges in the negative half-cycle	Discharge adjacent to a conductor at earth potential
	Similar pattern, but with the large impulses in the negative half-cycle	Discharge adjacent to a conductor at high voltage
	Near the inception voltage these discharges may be intermittent	
 (c)	Equally spaced impulses of about equal height at the negative crest of the applied voltage	Corona discharges around a sharp point at high voltage
	Equally spaced impulses of about equal height at the positive crest of the applied voltage	Corona discharges around a sharp point at low voltage
	The first impulse appears exactly at the crest of the applied voltage. This fact may be used for establishing the points of maximum voltage at the elliptical time base. A discharge standard according to Figure 3.12 may advantageously be used for this purpose	
 (d)	Irregular band of impulses, tending to occur around the zero points	Contact noise