Master course in High Voltage Engineering

Non-Destructive Insulation Test Techniques

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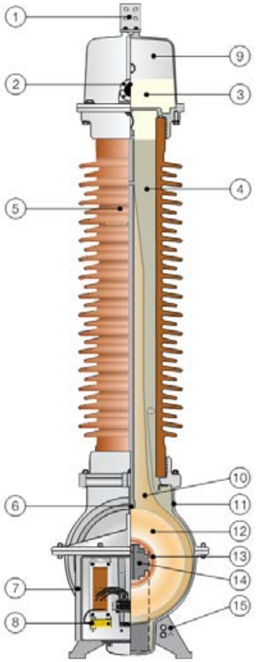
❖ What is a dielectric?

A kind of material used as electrical insulators which has a high electrical resistivity.

Gases: Atmospheric air, Sulphur Hexaflouride SF_6. Nitrogen and other mixtures under differnet pressures and temperature ……

Liquids:Transformer oil, synthetic esthers, silicone based fluids and other within HV apparatus as for instance power transformers and capacitors……

Solids: Porcelain, paper, wood, silicone rubber, different plastic materials as PEX, PVC ……



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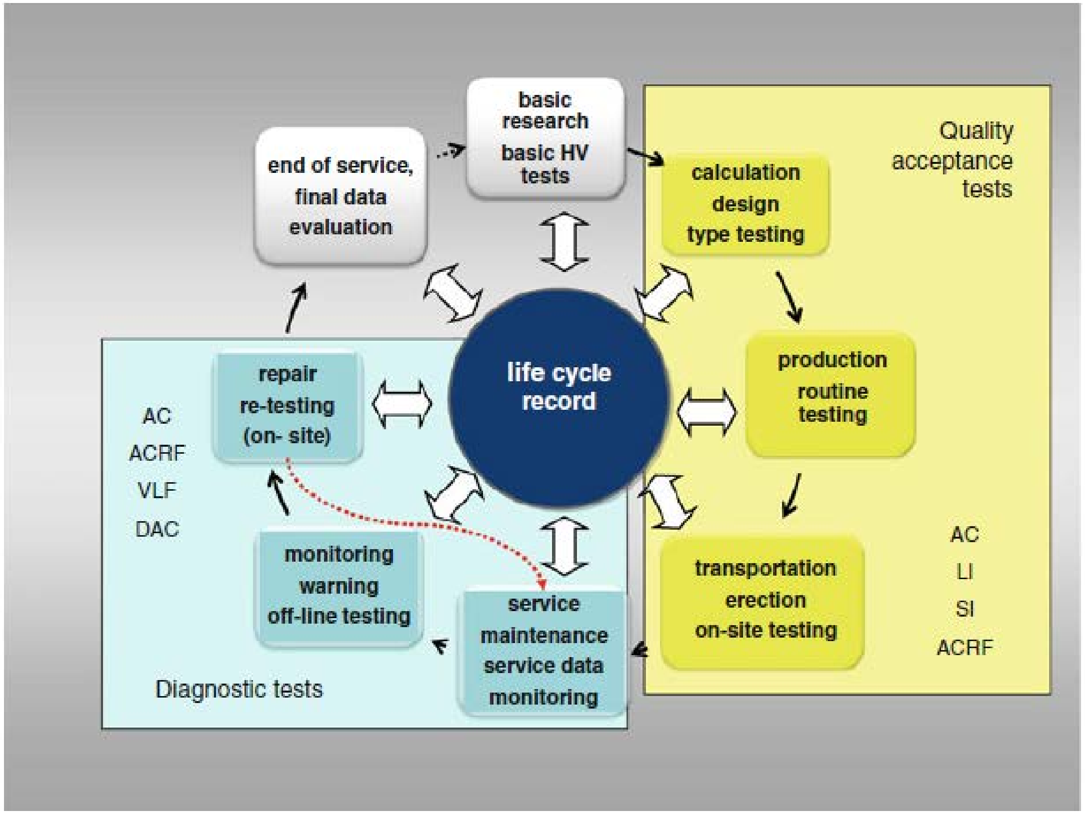
❖ Tests and measurements in the life cycle of HV insulation



❖ Electrical behaviors of dielectrics under electrical field

- Polarization (capacitance C, permitivity ε)
- Conductivity γ
- Partial discharge
- Electric strength: E

Non-destructive testing methods

Destructive testing methods

Destructive testing method: Applying voltage to the dielectric until it fails, which means the dielectric becomes conductive. The voltage at which the test object fails is the breakdown voltage which gives the upper voltage limit that it can stand.

Non-destructive testing methods: Discussed in the following slides.

❖ Important non-destructive HV test measuring quantities:

- DC conductive current, i_j[μA]
- AC dielectric dissipation factor (loss angle), tanδ
- AC partial discharges, q [pC]

❖ Parameters that affect the measuring quantities:

- The test voltage absolute value
- Temperature of the test object and surroundings
- The time, i.e. voltage waveform and influence time
- The properties of the dielectric in general (type of material, composition, purity…….)

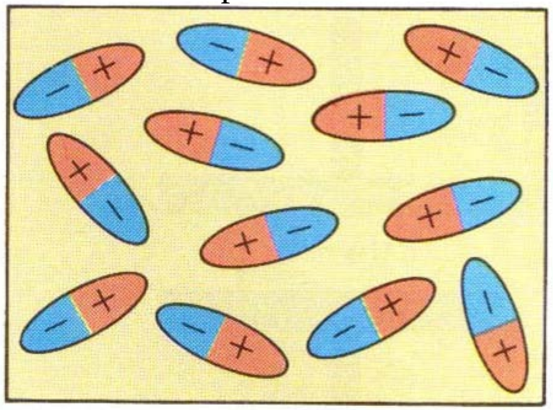
Dielectric Polarization

❖ Dielectric polarization

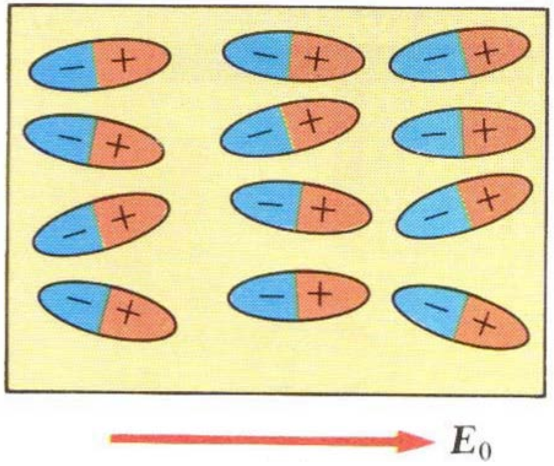
- At an atomic level, all matter consists of negative and positive charges balancing each other in microscopic as well as in macroscopic scales, thus an overall charge neutrality exists in the matter.

- When the matter is stressed by even a very weak external electric field, local charge imbalance is thus induced within the neutral species(atoms or molecules) as the centres of gravity for the equal amounts of positive and negative charges, ±q, become separated by a small distance, creating different kinds of dipole.

Unpolarized

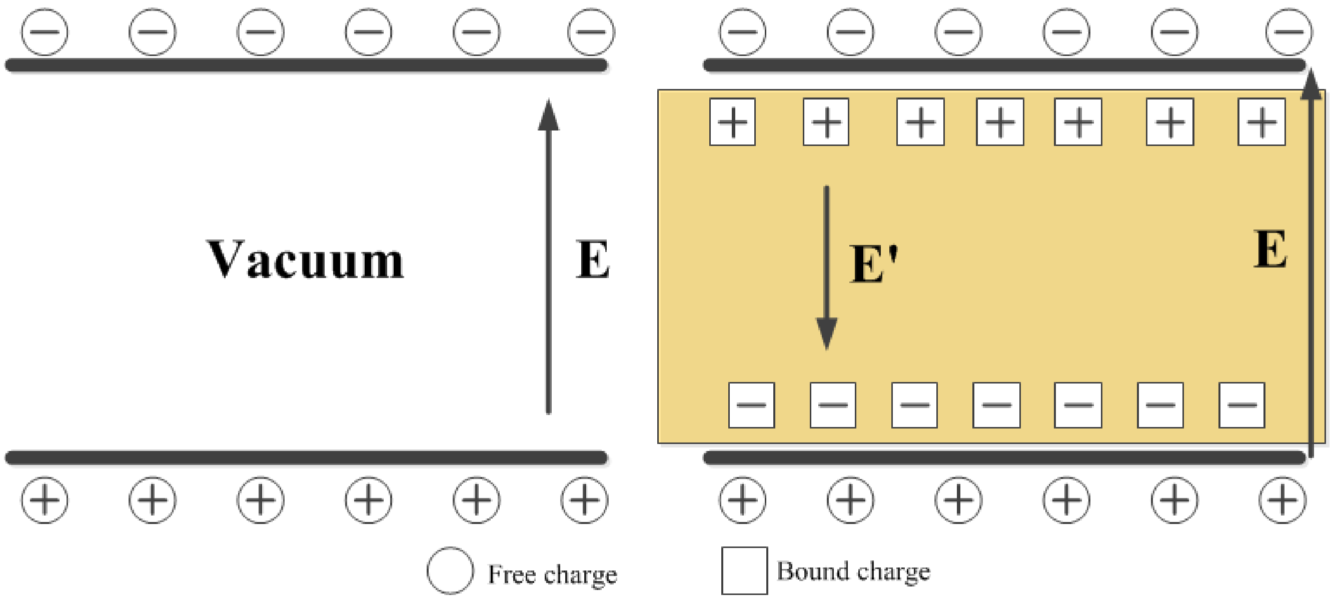


Polarized



Dielectric Polarization

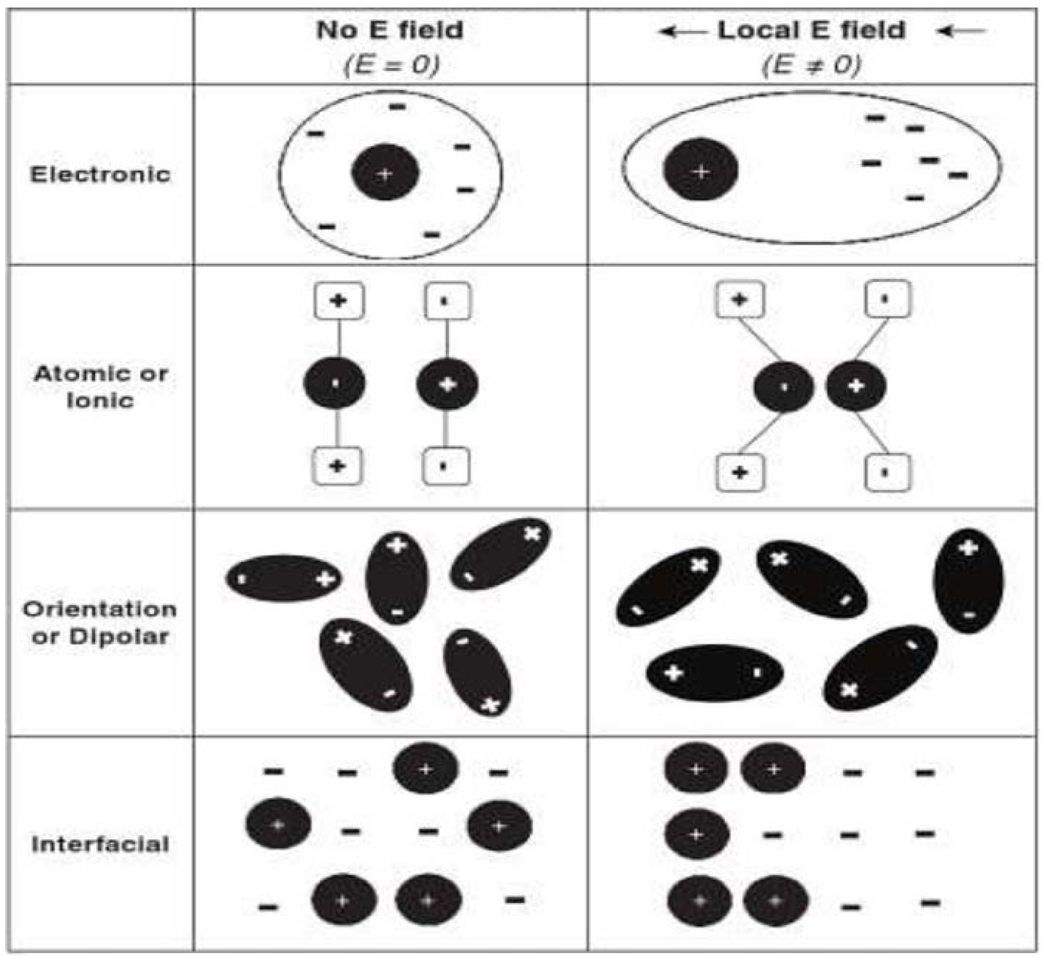
Application of polarization- capacitors



- Apply voltage U_0 to a capacitor with two metal plates in vacuum: $Q_0 = C_0 * U_0$;
- Remove the voltage source, insert a dielectric material between the plates, because of polarization, an opposite electrical field is established by bound charge. The real-time internal electrical field strength within the dielectrical material is: $E_1 = E - E'$;
- Thus the potential difference between the two plates after inserting the material is $U_1 = E_1$*d $= (E - E')$*d< U_0;
- Then $Q_0 = C_1 * U_1$; C_1 is the capacitance after inserting the material; Thus$C_0 * U_0 = C_1 * U_1$, $C_0 < C_1$, indicating the capacitance of the capacitor increases when inserting a dielectrica material.

Dielectric Polarization

❖ Different types of polarization



❖ Permitivity ε and relative permitivity ε_r

- To better explain the degree of polarization, we define ε, permitivity (also called dielectric constant), a factor indicating the polarizability of a dielectric material. The bigger it is(i.e. the bigger E' it is), the more easily the material can be polarized.

- An ideal dielectric will be completely lossless and its permitivity is a non-complex constant.

- Vacuum is considered as an ideal dielectric and has a permitivity:

$$\varepsilon_0 = 8.85 * 10^{-12} (F/m)$$

$$C_0 = \varepsilon_0 * \frac{A}{L}$$

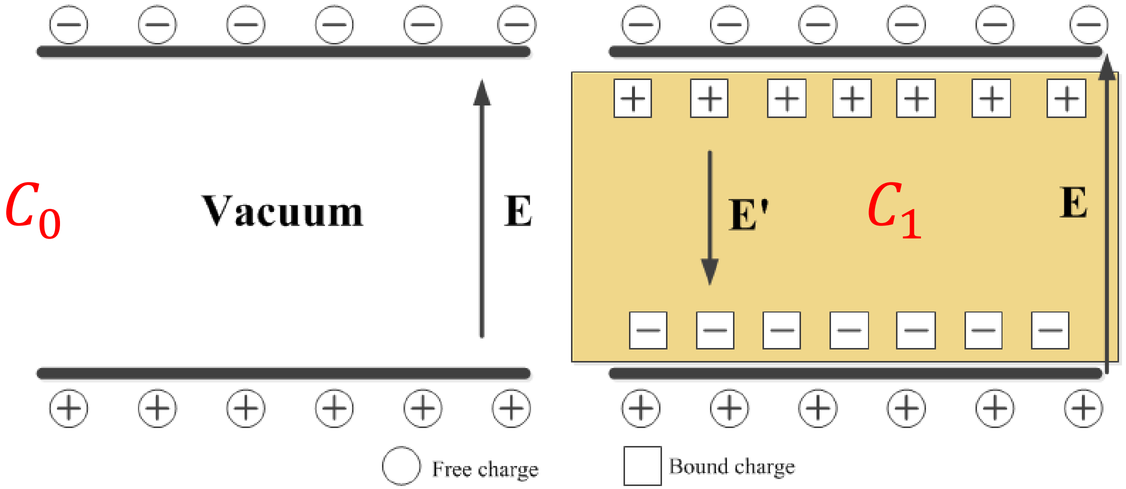
- Different dielectrics' permitivity and capacitance can be calculated as

$$\varepsilon = \varepsilon_0 \, \varepsilon_r$$

- In the case of constant fields and alternating fields of sufficiently low frequency the relative permitivity of an dielectric is equal to the ratio of the capacitance of a capacitor, in which the space between and around the electrodes is entirely and exclusively filled with the dielectric, to the capacitance of the same configuration of electrodes in a vacuum.

$$\varepsilon_r = \frac{C_1}{C_0},$$

$$C_1 = \varepsilon_r * C_0 = \varepsilon_r \varepsilon_0 * \frac{A}{L}$$



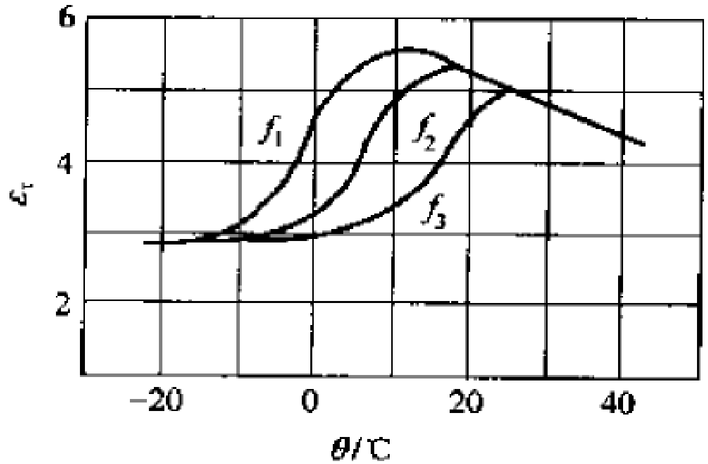
Relative permitivity ε_r

Relative permitivity of some materials at room temperature (around 20°C) under 1 kHz

Material	ε_r
Vacuum	1
Air	1.000585
Wood	2.8
Paper	3.85
Silicon	11.7
Ethyl alcohol	25.7
Sulfuric acid	84-100(20-25°C)
Water	81.5

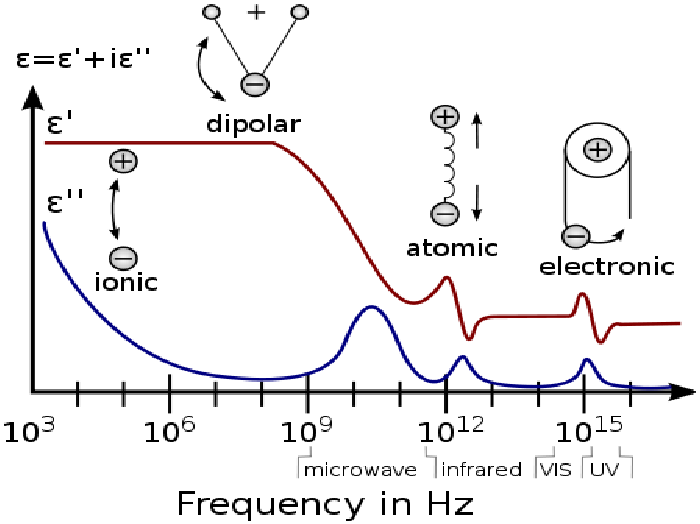
Usually, ε_r is related to frequency f and temperature T. Thus when talking about the relative permitivity of a specific dielectric material, the frequency and temperature must be stated.

❖ Relative permitivity ε_r related to temperature and frequency



$f_1 < f_2 < f_3$

Permitivity is a complex parameter if consider dielectric loss!

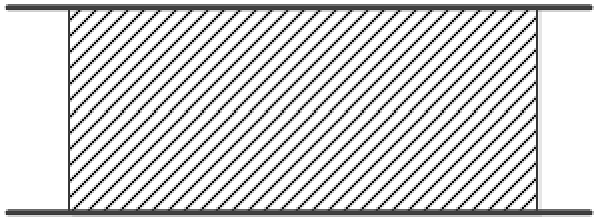


- IEC 62631 gives general guidelines for the determination of dielectric properties of solid electrical insulating materials.

Dielectric Polarization

❖ How to choose ε_r in industrial application?

- For insulating material used in capacitors, ε_r should be high thus we can get a large capacitance while a relative small capacitor volume;



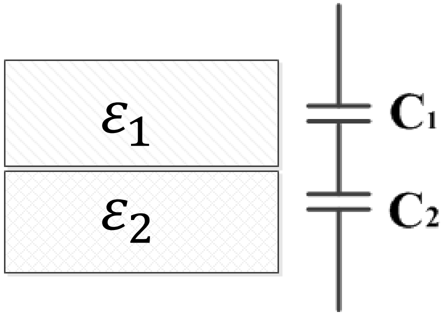
$$\varepsilon_1 = 2, \quad C = 2nF$$
$$\varepsilon_2 =? \quad C = 4nF$$

- For insulating material used in electrial devices, ε_r should be low since high ε_r usuallay comes with a high dielectric conductivity, which adds the energy loss; The usage of insulating material with low ε_r in power cables can decrease the charging current and increase the flashover voltage along the bushing surface.

❖ How to choose ε_r in industrial application?

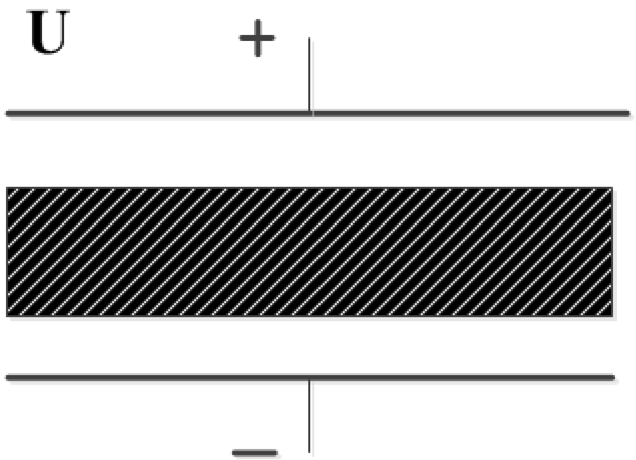
- When using different dielectrics as a combined insulation under AC or impulse, the chosen of ε_r of different dielectrics should be attached much importance to. With AC or impulse voltage, the electrical field strength within the dieletric which has the lowest ε_r is the highest. That means the distribution of voltage on a combined insulation is depended on the inverse of the ratio of their relative permitivity:

$$\frac{U_1}{U_2} = \frac{C_2}{C_1} = \frac{\varepsilon_2}{\varepsilon_1}$$



Exercise 1

- A voltage U=55 kV at power frequency is applied to a plate-electrode capacitor with air ($\varepsilon_1 = 1$) as the medium. The distance between the plates is 2cm. Then capacitor doesn't breakdown.
- Then insert a 1cm thick PE (polyethylene) plate ($\varepsilon_r = 2.3$) between the electrodes.



Question: Whether the air between the electrodes breakdown or not after inserting the PE ?

hint: $C = \varepsilon * \frac{A}{d}$, A is the dielectric surface area and d is the thickness;

The electric strength of air is 30 kV/cm

Dielectric Polarization

❖ Characteristics of different polarizations

Type of polarization	Where	Time for polarization [s]	Reasons	Energy loss
Electronic	All dielectrics	10^{-15}	Displacement of bound charge	No
Inoic	Ionic dielectric	10^{-13}	Displacement of ions	Almost no
Dipolar	Dielectrics with permanent dipoles	$10^{-10} - 10^{-2}$	Re-orientation of dipoles	Yes
Interfacial	Interfaces of different dielectrics	10^{-1}-hours	Shif of free charges	Yes
Space charge	Around electrodes			Yes

Equivalent circuit of dielectrics

❖ Dielectric conductivity γ

- An ideal dielectric only comprises a capacitance. However, practical real-life dielectrics will always include some charged particles (for instance, impurity ions). When the dielectric exposed to a electrical field, the movable charge particles can form a vey small current. This phenomenon is called the dielectric conductivity γ.
- And the small current is called leakage current.
- The dielectric conductivity γ is very small, range from $10^{-16}\sim10^{-10} S/m$.
- The solid dielectrics have volume conductivity and surface conductivity. The contamination and humidity on the solid dielectric surface have great effects on the surface conductivity of the dielectrics.

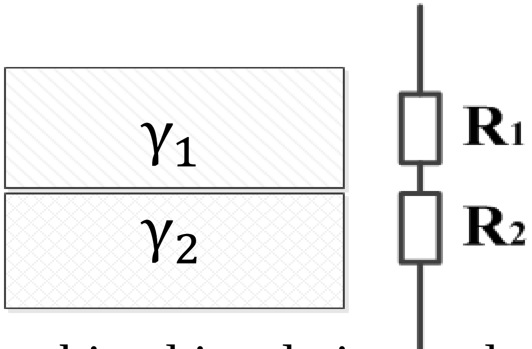
❖ How to calculate conductivity γ

$$R = \rho * \frac{L}{A}$$

$$\gamma = \frac{1}{\rho} = \frac{L}{R * A}$$

R is the electrical resistance of a uniform specimen of the material(Ω), ρ is the electrical resistivity (Ω•m), L is the length of the piece of material, A is the cross-section area of the specimen.

$$\frac{U_1}{U_2} = \frac{R_1}{R_2} = \frac{\gamma_2}{\gamma_1}$$



- When using different dielectrics as a combined insulation under DC, the distribution of voltage on the insulation is depended on the inverse of the ratio of their conductivity

❖ Dielectric conductivity γ

Conductivity γ of some materials at room temperature (around 20°C)

Material	$\gamma\ (S \bullet m^{-1})$
Air	3×10^{-15} to 8×10^{-15}
Drinking water	5×10^{-4} to 5×10^{-2}
Silicon	1.56×10^{-3}
wood	10^{-4} to 10^{-3}
Hard rubber	10^{-14}
Fused quartz	1.3×10^{-18}
PET	10^{-21}
Teflon	10^{-25} to 10^{-23}

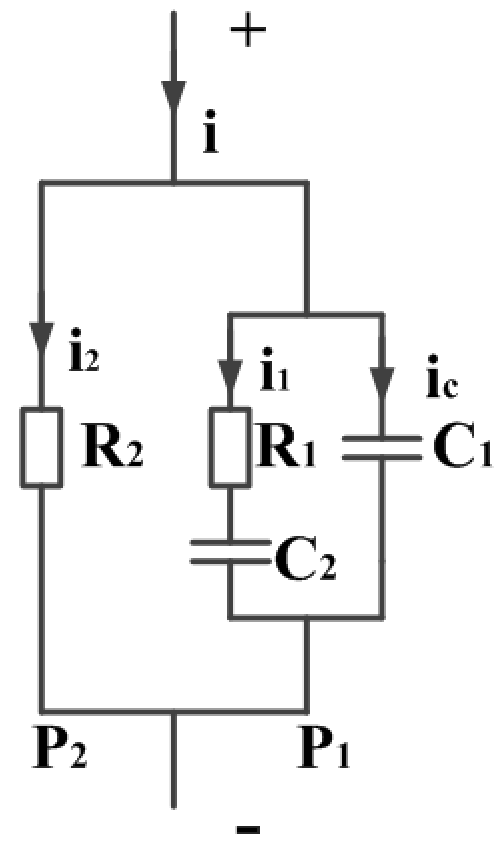
- γ increases as the temperature increases.

Equivalent circuit of dielectrics

❖ Equivalent circuit of dielectrics (PD is not considered here)

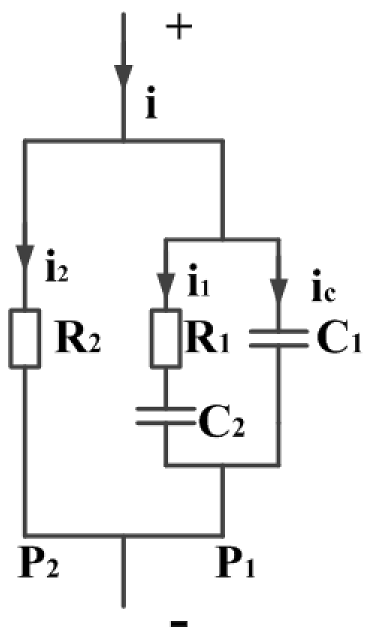
- An ideal dielectric only comprises the capacitance $C = C_1 + C_2 + \cdots C_n$;
- The polarization losses causes a real component of the capacitive current, which is simulated by means of R_1;
- Practical real-life dielectrics always include charged particles which form leakage current, this can be simulated by the resistor R_2 ;
- When the dielectric exposed to a electrical field, the current flow through it can be indicated as

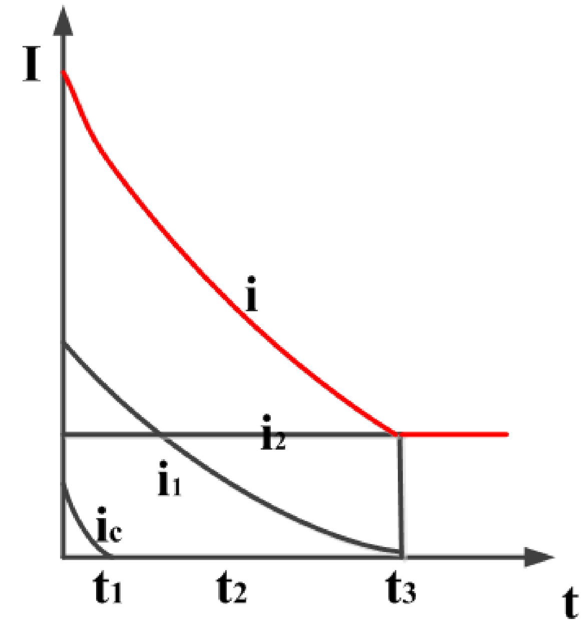
$$i = i_c + i_1 + i_2$$



Equivalent circuit of dielectrics

❖ Measurement of DC conductive current, i_j[μA]

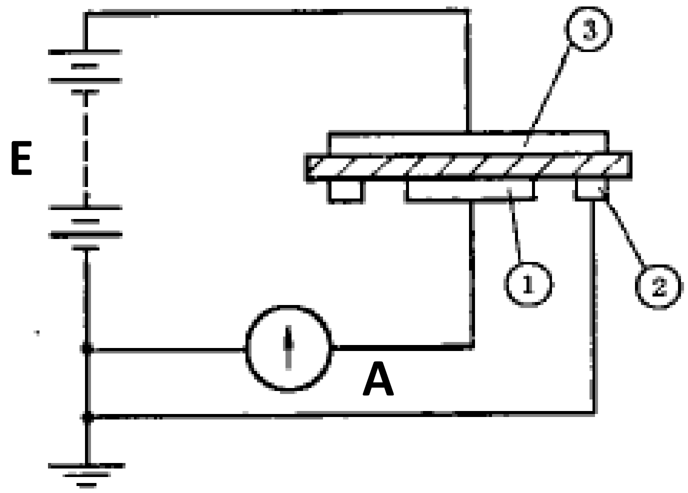




- Polarization current without loss i_c disappears quickly (10^{-15}~10^{-13}s);
- Polarization current with loss i_1 (absorbtion current) disappearly much more slowly ($10^{-10}s$~ even hours);
- Conductive current (leakage current) i_2 (i_j) always exists.

Equivalent circuit of dielectrics

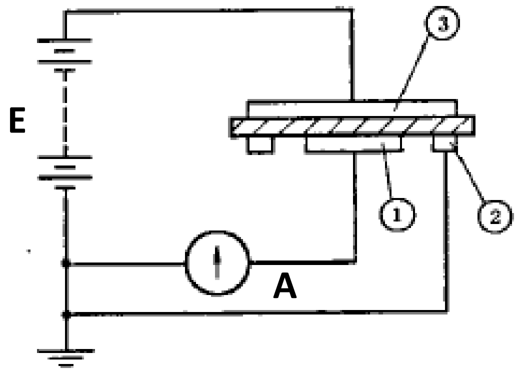
❖ DC conductive current measurement circuit

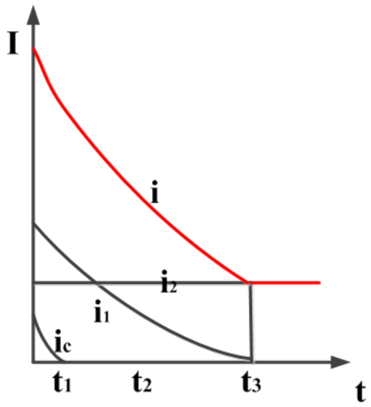


- E is the DC voltage source;
- A is a highly sensitive ammeter in the pA- nA range;
- 1- protected electrode, 2-guard electrode, 3-unprotected electrode;

- Current along the surface is excluded by the guard electrode;
- Possible polarization phenomena at electrodes are neglected.

❖ Conductivity calculation

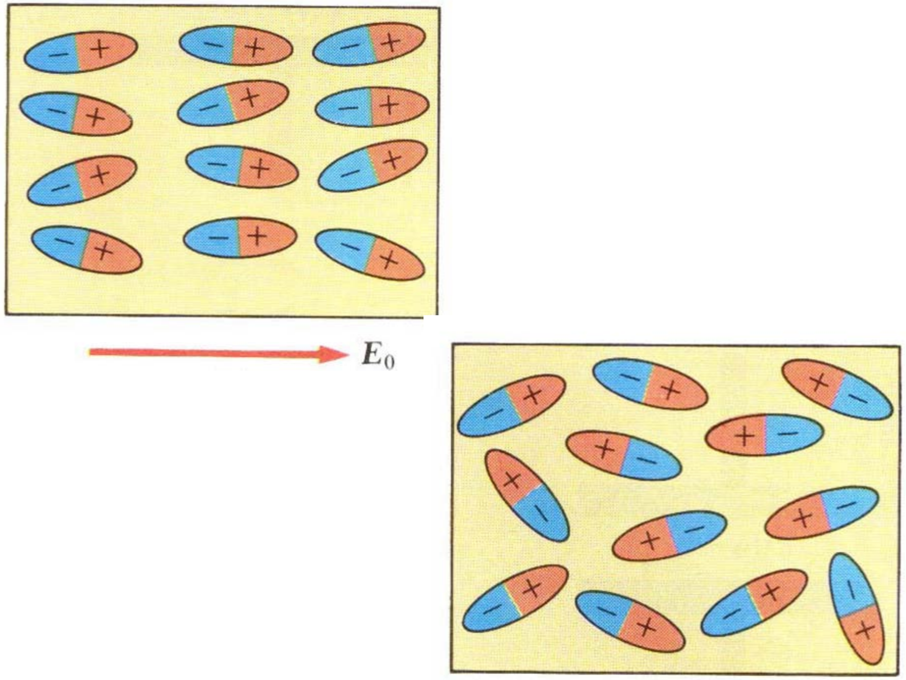


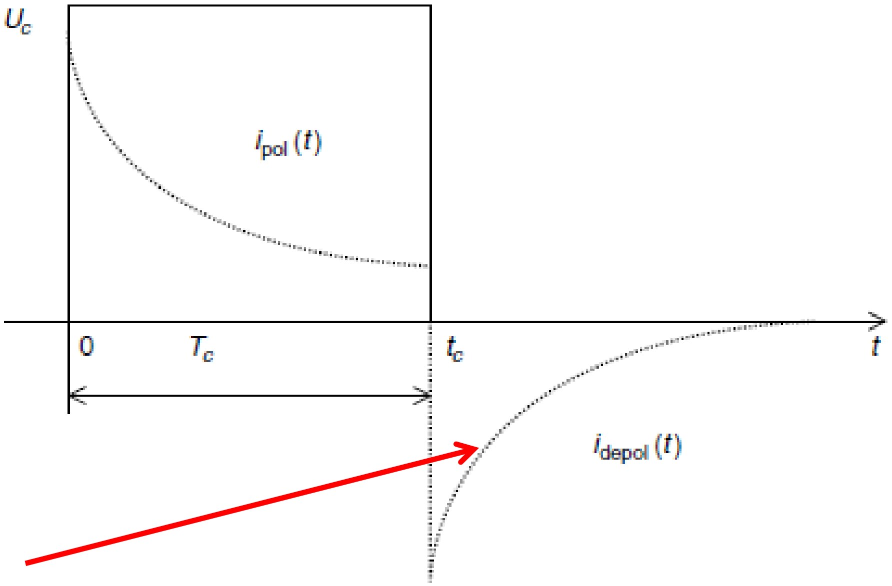


- Appyling DC voltage U at the dielectric for a period (minutes or hours);
- After a certain period, measure the leakage current, i.e. the conductive current i_j
- Use Ohm’s law to calculate the insulation resistance : $R_2 = {}^{U}/_{i_j}$
- Conductivity can be calculated using R_2,L and A

$$\gamma = \frac{1}{\rho} = \frac{L}{R * A}$$

❖ Depolarization

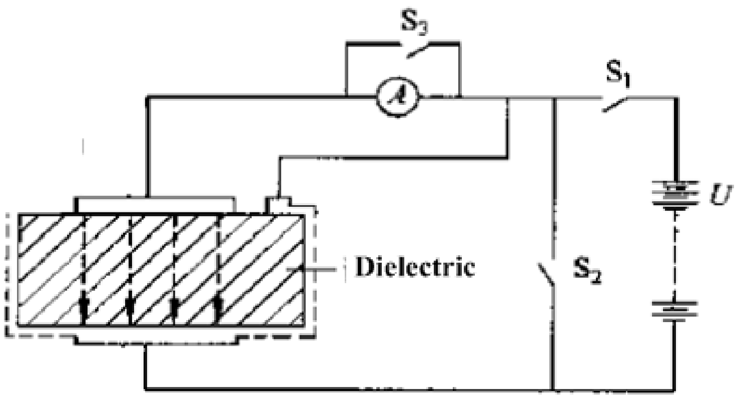


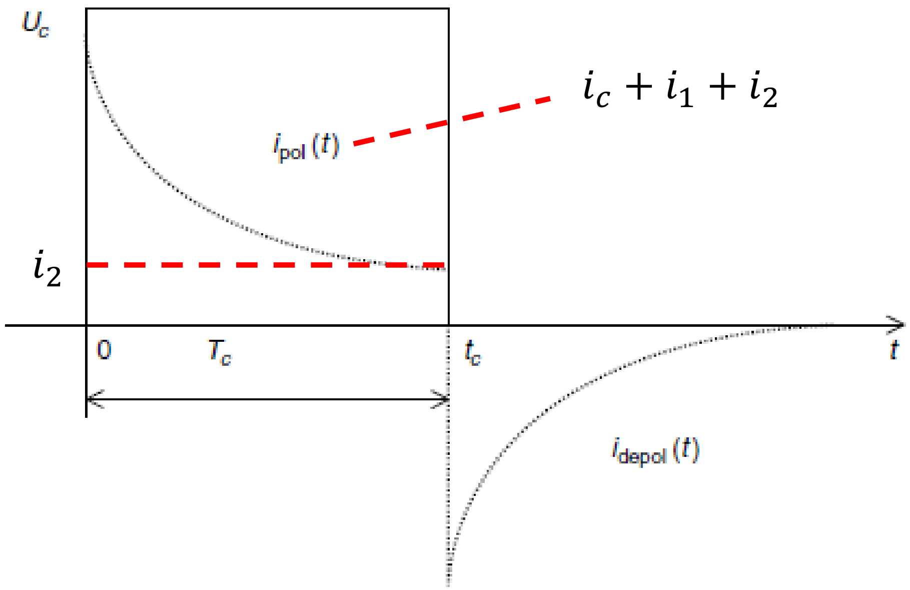


- After disconnect the voltage source, depolarization happens in the dielectric because of re-shift or re-movement of dipoles/charges;
- A depolarization current (or relaxation current) can be measured;
- The measurement of depolarization current is a new method to evalute the aging condition of HV insulation.

Equivalent circuit of dielectrics

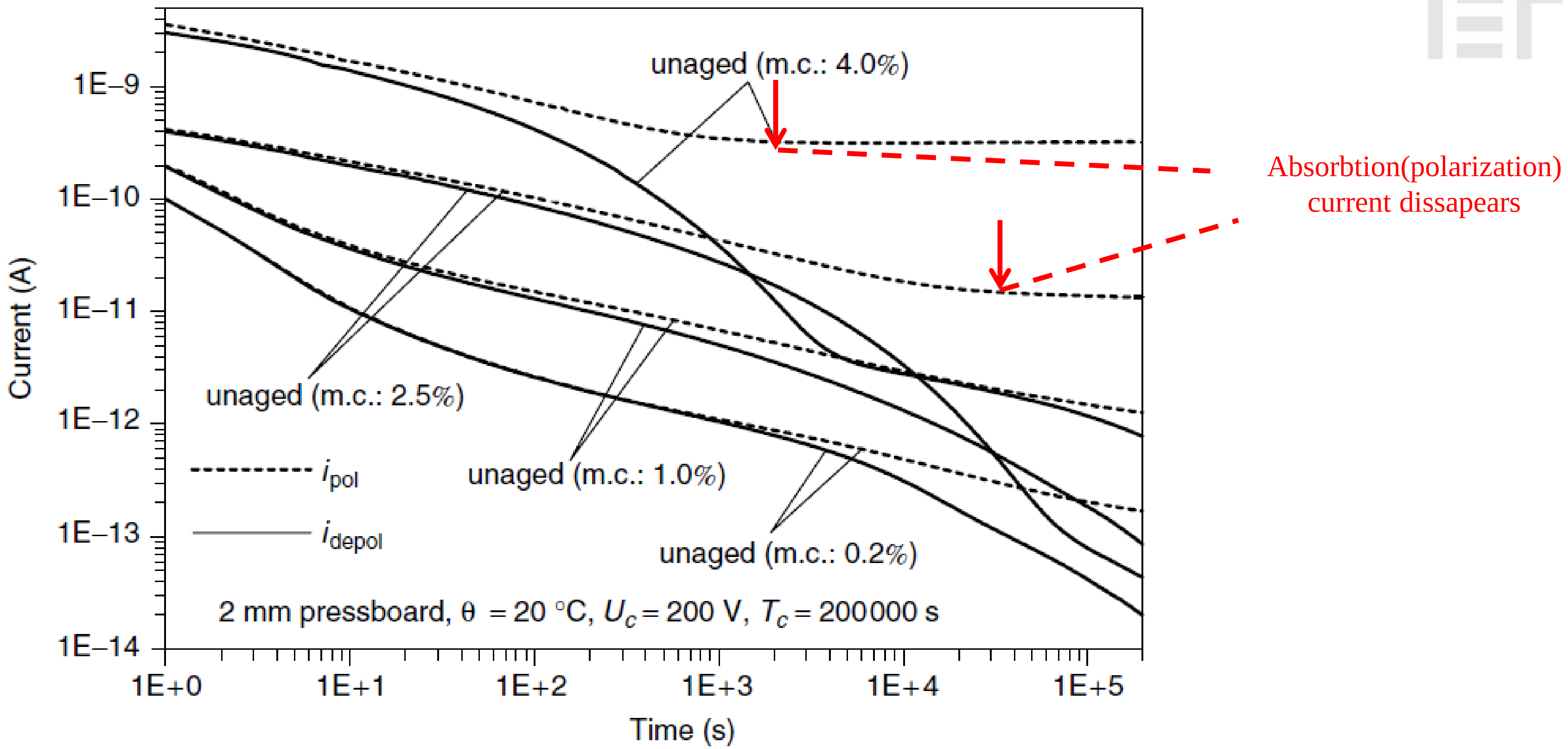
❖ Measurement of depolarization current





- Appyling DC voltage U_C at the dielectric between $0 < t < t_c$, i.e. switch on S_1 and switch off S_2 between $0 < t < t_c$;
- Short circuit the dielectric when $t \geq t_c$, i.e. switch off S_1 and switch on S_2 when $t \geq t_c$;
- The ammeter measures the current flows through the dielectric (in the right figure).

Equivalent circuit of dielectrics

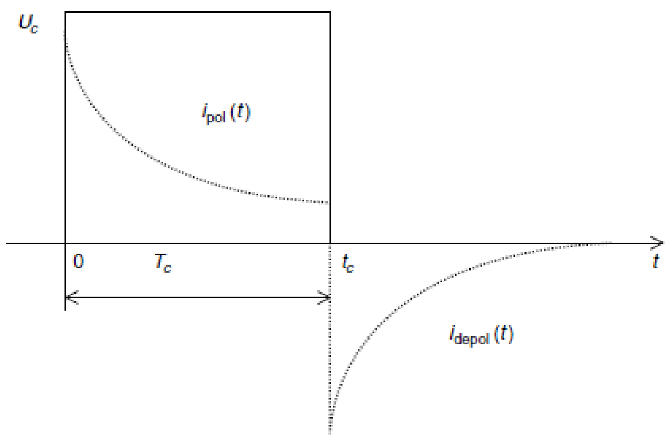


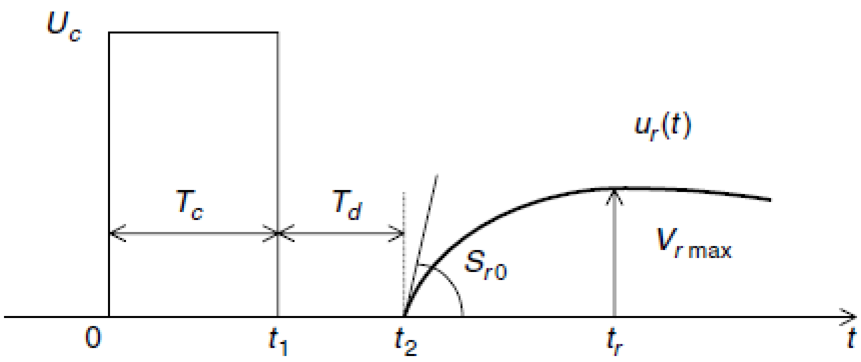
Dielectric response of oil-paper insulation with different moisture content(m.c.)

- The final value of the polarization current is reached only for higher mosture content;
- This method, Dielectric response analysis (DRA, also called PDC method), is used as in-service monitoring of insulation.

Equivalent circuit of dielectrics

❖ Recovery voltage





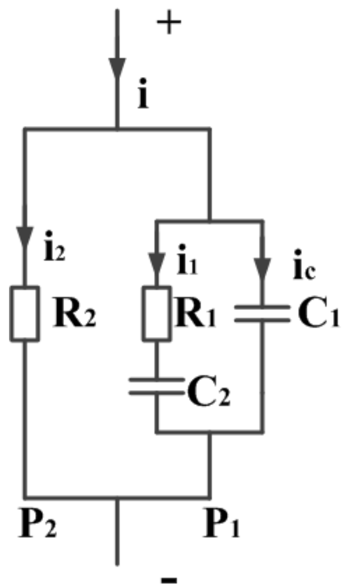
- Appyling DC voltage U_C at the dielectric between $0 < t < t_1$, i.e. switch on S_1 and switch off S_2 between $0 < t < t_1$;
- Short circuit the dielectric between $t_1 < t < t_2$, i.e. switch off S_1 and switch on S_2 between $t_1 < t < t_2$;
- Switch off S_2 when $t \geq t_2$;
- A <u>recovery voltage</u> $u_r(t)$ is measured between the dielectric after switch off S_2.

Question

Why the grouding stick needs to be kept at the HV terminal of capacitors in HV lab after experiments end?

Measurement of AC dissipation factor

❖ Dielectric losses



- As discussed before, practical real-life dielectric has a complex permitivity because of dielectric losses.

$$\tilde{\varepsilon_r}(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega);$$

$\varepsilon'(\omega)$ corresponds to capacitance, $\varepsilon''(\omega)$corresponds to dielectric losses (dielectric loss index).

- The current flow through the dielectric can be calculated as:

$$I = j\omega CU + \frac{U}{R}$$

C is the equivalent capacitance of the dielectric, R is the equivalent resistor of the dielectric, U is the applied voltage, ω is the angular frequency of the voltage.

$\bar{S}$ is the current density.

$$\begin{cases} C = \tilde{\varepsilon_r} * C_0, C_0 = \varepsilon_0 * \dfrac{A}{L} \\ R = \dfrac{1}{\gamma} * \dfrac{L}{A}, U = E * L \\ \bar{S} = \dfrac{I}{S} \end{cases}$$

- A dielectric between electrodes connected to AC voltage source will posess an electrostatic field E giving rise to a current density of:

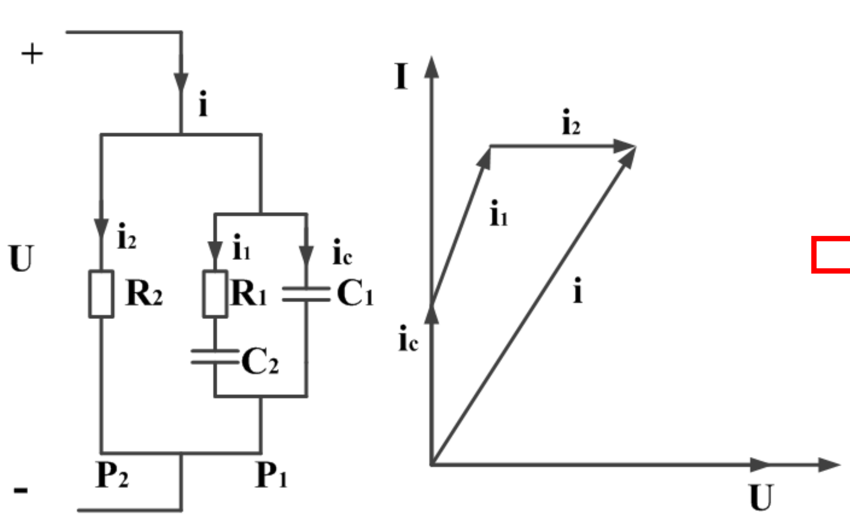
$$\bar{S} = (\gamma + \omega\varepsilon_0\varepsilon'')E + j\omega\varepsilon_0\varepsilon' E$$

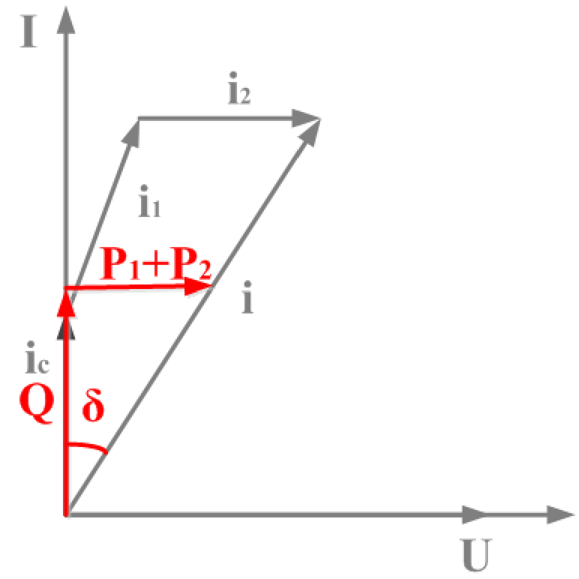
The imaginary part represents the reactive current, while the real part represents active current. In other words, the real part represnts the dielectric losses (including conductive loss and polarization loss). The dielectric dissipation factor is defined as ratio of active current to reactive current:

$$tan\delta = \frac{I_a}{I_{re}} = \frac{(\gamma + \omega\varepsilon_0\varepsilon'')}{\omega\varepsilon_0\varepsilon'} \approx \frac{\varepsilon''}{\varepsilon'}$$

Measurement of AC dissipation factor

❖ Dielectric losses





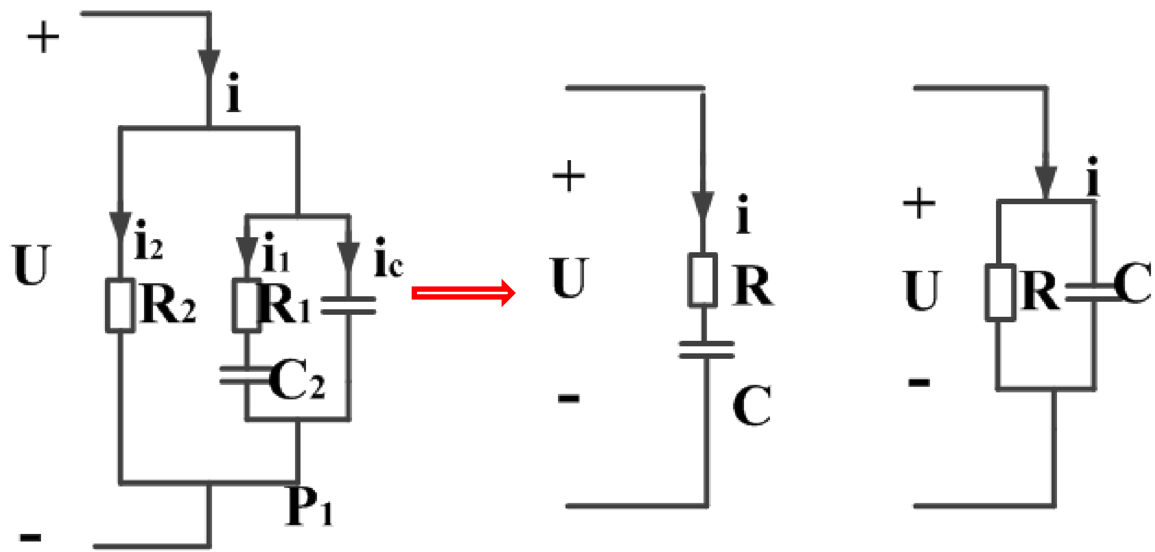
Practical real-life dielectric always have losses which are comprised of :

- Conductive loss
- Polarization loss
- Ionization loss (not discussed here)

$$tan\delta = \frac{I_a}{I_{re}} = \frac{P_1 + P_2}{Q}$$

Measurement of AC dissipation factor

- Measurement of AC dissipation facotr, tanδ



Series equvalence

Parallel equvalence

Series equivalence:

$$tan\delta = \omega RC$$

Parallel equivalence:

$$tan\delta = \frac{1}{\omega RC}$$

Measurement of AC dissipation factor

❖ Shering bridge in series equivalent circuit

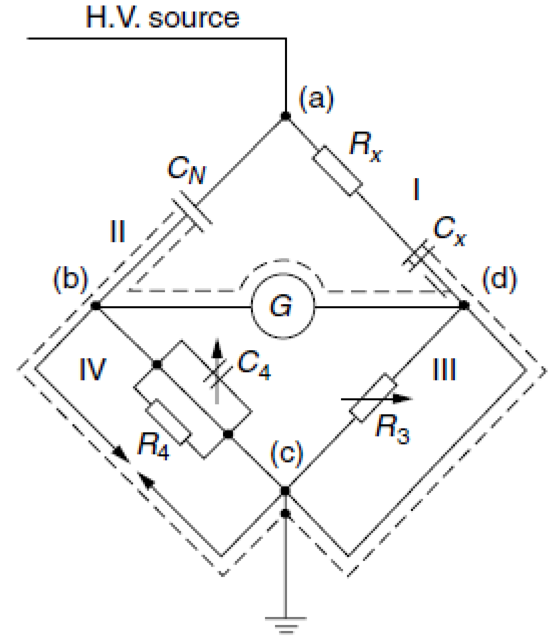
- One of the most commonly used methods for measuring dissipation factor and capacitance with high precision.

- C_N: Standard HV capacitor

  C_x and R_x: test object

  R_3, C_4: variable resistor & virable capacitor

  G: Null detector

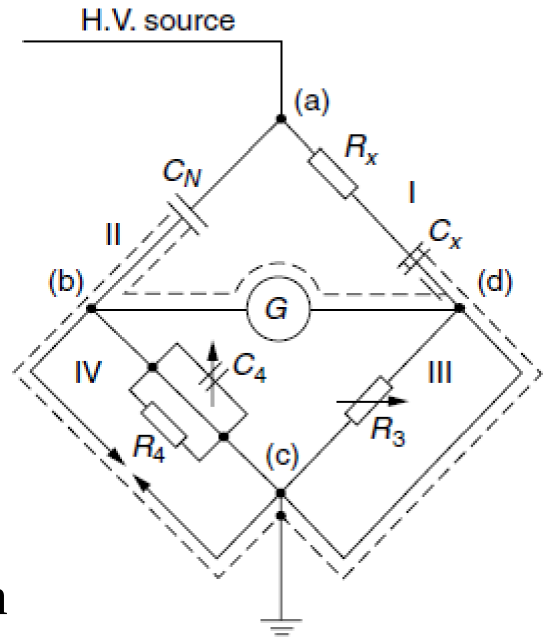


When the 'G' indicates zero:

$$\frac{Z_{ab}}{Z_{bc}} = \frac{Z_{ad}}{Z_{dc}} \qquad \begin{cases} Z_{ad} = R_x + \dfrac{1}{j\omega C_x}, Z_{ab} = \dfrac{1}{j\omega C_N} \\ Z_{bc} = \dfrac{1}{\dfrac{1}{R_4} + j\omega C_4}, Z_{dc} = R_3 \end{cases}$$

Measurement of AC dissipation factor

❖ Shering bridge in series equivalent circuit



$$\begin{cases} C_x = C_N \frac{R_4}{R_3}, \ R_x = R_3 \frac{C_4}{C_N} \\ tan\delta = \omega R_x C_x \end{cases}$$

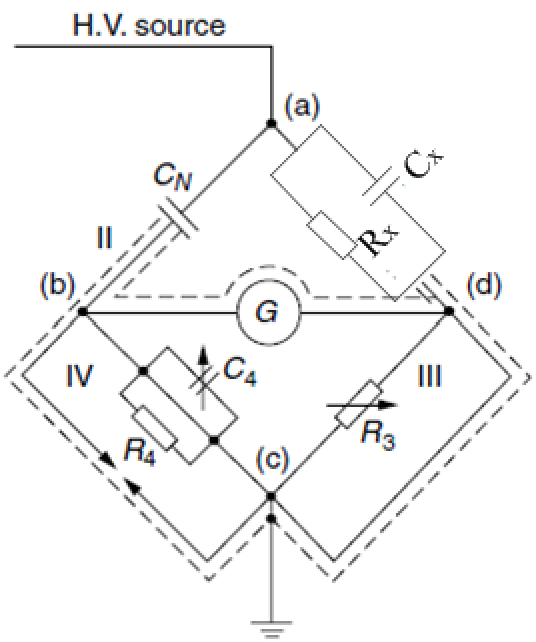
$$tan\delta = \omega R_4 C_4$$

The applied normal capacitor C_N has to be a very high quality component. The bridge determination is based on assuming Cn has very low and nearly negligible loss over a wide frequency range.

Exercise 2

- If we consider the dielectric in the parallel equivalent circuit, how to calculate the dielectric factor tanδ and the capacitance C_x?

$$tan\delta = ??$$
$$C_x = ??$$

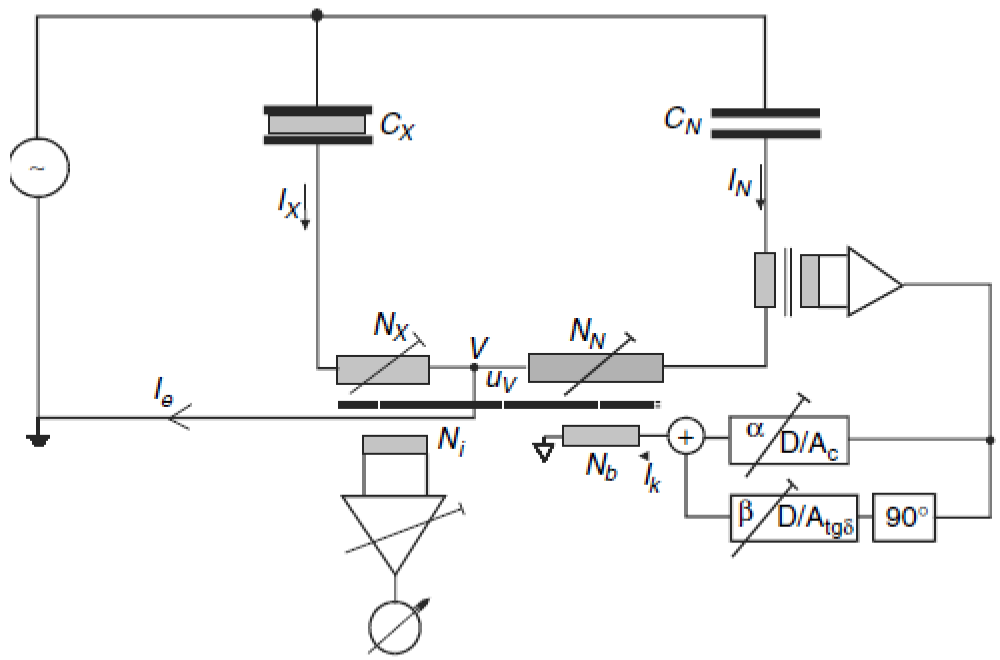


Measurement of AC dissipation factor

Measurement of AC dissipation factor

Measurement of AC dissipation factor

- Fully automatic self-banlacing bridge



$$U_t N_x \left(j\omega C_X + {}^{1}/_{R_x}\right) = U_t j\omega C_N (N_N + k(\alpha - j\beta) N_b)$$

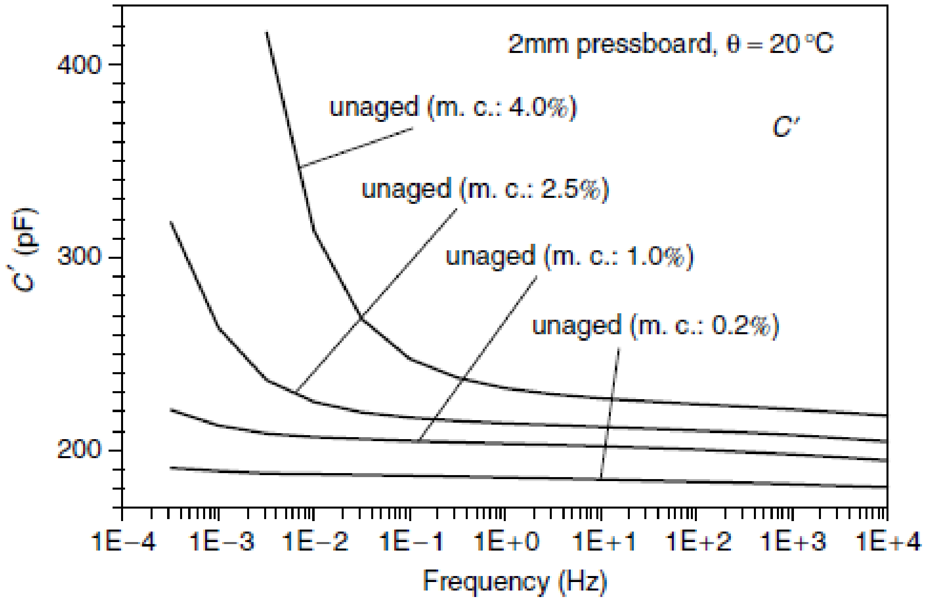
Measurement of AC dissipation factor

Capacitance and Dissipation Factor Measuring Bridge TG-3MOD

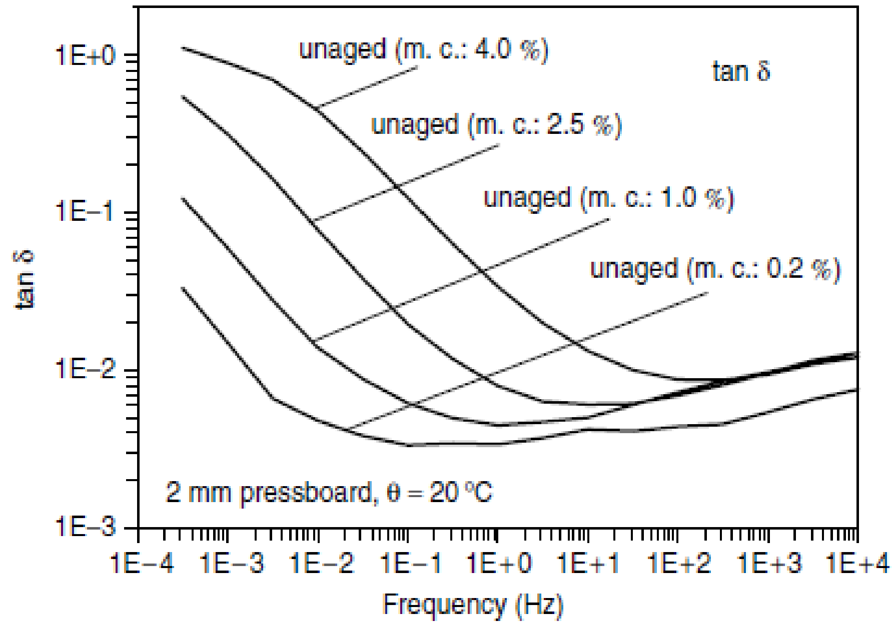
- fully automatic capacitance and power factor measuring bridge
- For high voltage insulation diagnostics
- 1... 2 x 10^{-5} uncertainty and 10^{-7} resolution for dissipation factor measurement
- measures impedances in all four quadrants
- built-in RS232 interface
- Options: Higher Cx - current range
  Automatic interference rejection

Measurement of AC dissipation factor

❖ Dielectric response at frequency domain:



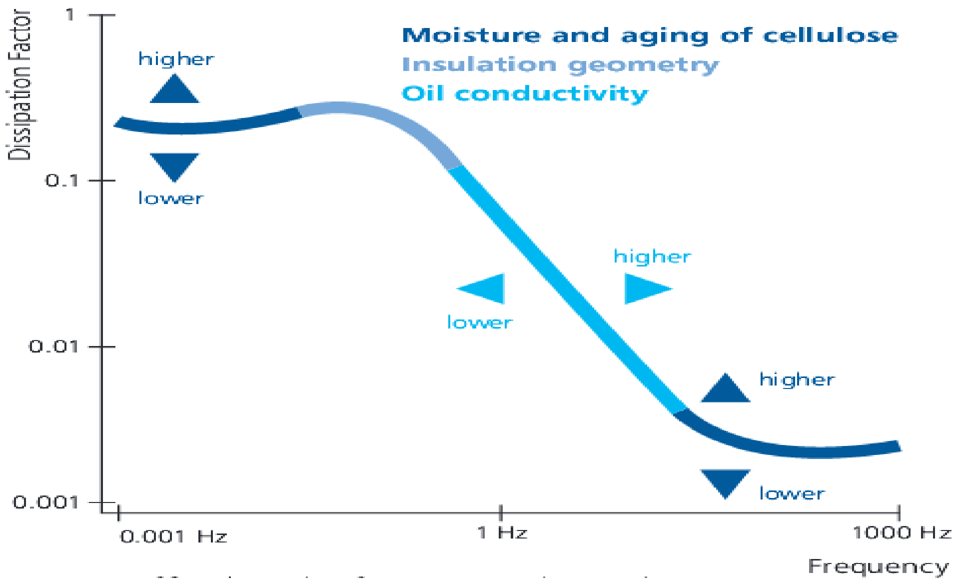
$\varepsilon'(\omega)$



$\varepsilon''(\omega)$

- The increased moisture content in a dielectric or an insulation system results in changed dielectric response, which can indicate the insulation condition or the aging condition. Thus through measuring the dielectric response in a wide frequency range, the insulation condition or aging condition of the dielectric or insualtiong system can be evaluated.

❖ Dielectric spectroscopy test



- Frequency range: 10 Hz – 1000 Hz. Dominated by the cellulose insulation, cables and connection techniques.
- Frequency range: 0.01 Hz – 1 Hz. Dominated by the oil conductivity.
- Frequency: 0.003 Hz. Dominated by insulation geometry.
- Frequencies bellow 0.0005 Hz. Dominated by the cellulose insulation


ABB