● Non-destructive High Voltage test methods

The upper voltage limit for non-destructive HV testing is given by the breakdown voltage of the test object.

Creating a violent breakdown of any insulating device (mostly solid dielectrics) will only give knowledge about:

- The breakdown voltage
- The traces (remains !) after the breakdown

This will give no knowledge of the cause of the destroying breakdown

To avoid breakdown and thereby destruction of the test object it is possible to apply non-destructive HV test methods and still gain detailled knowledge of the condition of the test object.

● Dielectric insulating materials

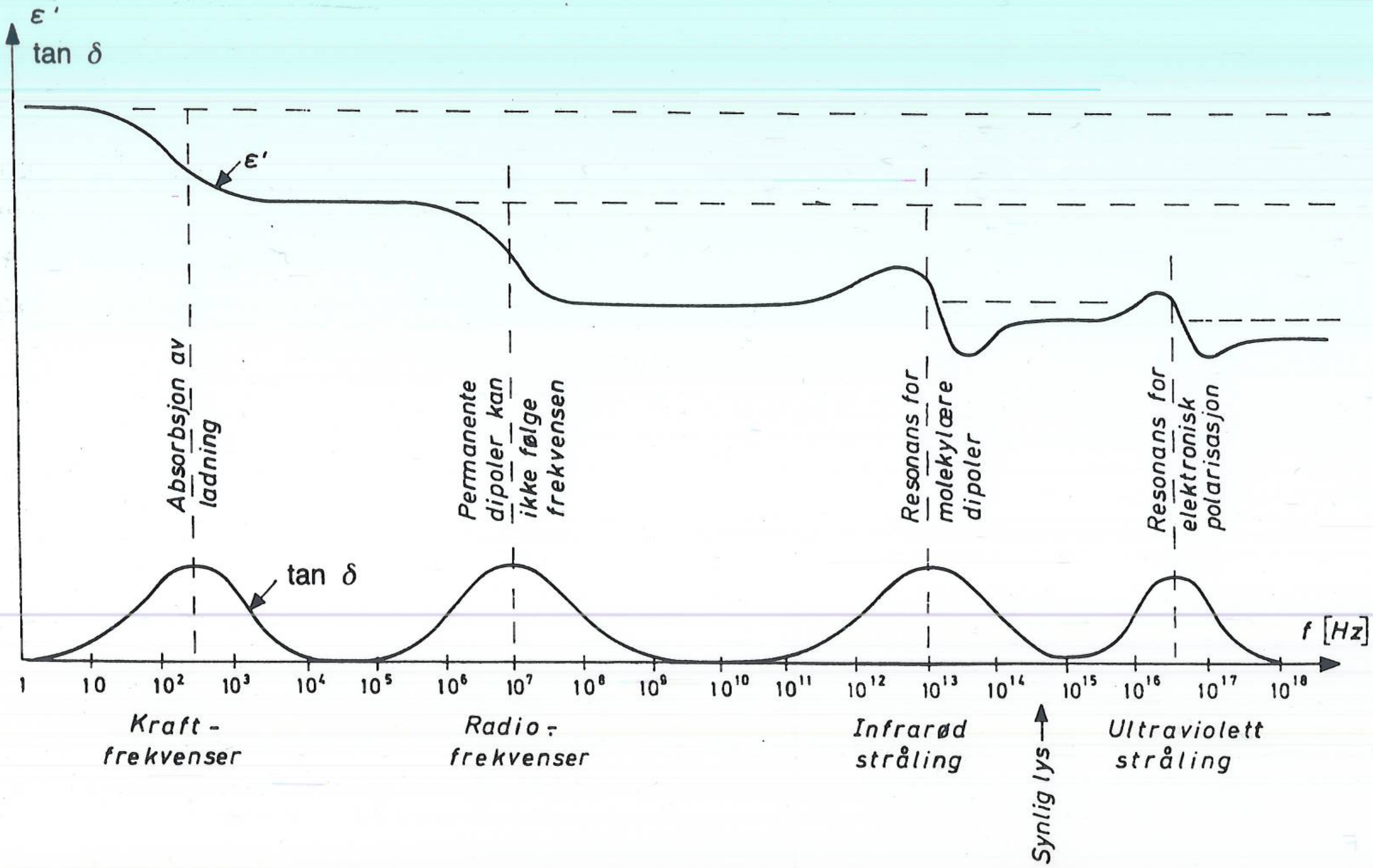
Gaseous: Atmospheric air, Sulphur Hexaflouride SF_6, Nitrogen and other mixtures under different pressures and temperature.

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

Solid: Porcellain, wood, paper, Quarts silica, silicone rubber (EPDM), different plastic materials as PEX, PVC a.o. in cables and elektrical machines.

The breakdown voltage of a solid dielectric will depend of the long time variance of the applied voltage.

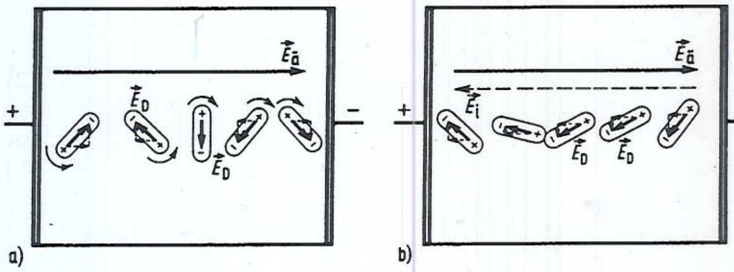
- ELECTRICAL BREAKDOWN FOR $7 \times U_N$, IMPULSE 1,2/50 μs
- THERMAL BREAKDOWN FOR $2 \times U_N$, POWER FREQUENCY 50 Hz



3.2.10 Frekvensavhengighet for dielektriske tap og permittivitet.

Tafel 1.19 Dielektrizitätszahl ϵ_r bei 20 °C, Verlustfaktor d = tan δ (50 Hz, 20 °C) und Durchschlagfeldstärke E_d verschiedener Isolierstoffe nach [2], [18], [23], [24]

Isolierstoff	Dielektrizitätszahl ϵ_r	Verlustfaktor $10^3 \cdot \tan\delta$	Durchschlagfeldstärke E_d in kV/cm
Porzellan	5 bis 6,5	17 bis 25	340 bis 380
Steatit	5,5 bis 6,5	2,5 bis 3	200 bis 300
Hartpapier	4 bis 7	20 bis 100	300 bis 600
Papier imprägniert	4 bis 4,3	5 bis 10	500 bis 600
Epoxidharz	2,8 bis 5	3 bis 10	200 bis 400
Polyesterharz	3,5 bis 5	3 bis 50	200 bis 290
Polyvinylchlorid	4 bis 5	50 bis 80	150 bis 500
Polyäthylen	2,3 bis 2,4	0,2 bis 0,3	200 bis 600
Hartgummi	2,5 bis 5	2 bis 6	200 bis 300
Mineralöl	2,2 bis 2,6	– bis 10	200 bis 300
Chlophen	4,5 bis 7	– bis 2	150 bis 250



1.20 Orientierungspolarisation im dielektrischen Werkstoff
a) statistisch verteilte Dipole
b) orientierte Dipole

1. Connect voltage $U_0 \Rightarrow Q_0 = C \cdot U_0$ to a capacitor in vacuum. Disconnect source.
2. Fill the gap with a dielectric.
3. This dielectric will undergo dielectric polarisation – dipoles will expirience a TORQUE!
4. The External field $\vec{E}_a$ will be opposed by internal field $\vec{E}_i$ $\Rightarrow$ resulting in $E = E_a - E_i$ and voltage lowers as Q_0 = constant.
5. Displacement D non-changed so $D = \varepsilon_0 E_a = \varepsilon_0 \varepsilon_r (E_a - E_i) \Rightarrow$

$$\varepsilon_r = \frac{1}{1 - E_i/E_a}$$

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Dept. of Power Systems and High Voltage Engineering

● Dielectric losses

An ideal dielectric will be completely lossless and its appearance in an electrical field can be described by means of a real non-complex dielectricity constant:

$$\varepsilon = \varepsilon_o \cdot \varepsilon_r \qquad \varepsilon_o = 8{,}85 \cdot 10^{-12}\ F/m$$

Practical real-life dielectrics will always include some losses. The physical explanations for these losses are:

- Conductive losses P_1, caused by ionic- or electronic conduction. The conductivity of a dielectric will reach a final value γ.

- Polarization losses P_p, orientation- border- or deformative polarization.

- Ionisation losses P_i, partial discharges within or on insulating systems (Teilentladungen, TE).

The ~~above-mentioned~~ losses creates/generates different electrical phenomena which can be used to separate them by means of non destructive HV test methods.

Important non-destructive HV test measuring quantities are:

- DC conductive current i_j [μA].

- AC loss angle, tg δ.

- AC partial discharges, q [PC].

These quantities are all dependent of many different parameters.

Parameters which affect the measuring quantities are:

- The test voltage absolute value.
- Temperature of the test object and the surroundings.
- The time, ie. voltage waveform and influence time.
- The properties of the dielectric in general.

Important material properties are:

- Type of material, composition, structure, purity, temperature, prehistory. Especially the prehistory (the life of a transformer = operational conditions) is very decisive for the condition of the insulating system of a power transformer.

The lifetime of expensive HV apparatus like transmission level power transformers is worth predicting to be able plan investment, ordering and operation of large power systems.

Table 1 Summary of transformer tests

Test	Faults detected	Location of fault	Cost & Convenience	Use
Dissolved Gas Analysis	Discharge Overheating	None (integrates over time)	Cheap & easy On-line	Routine
Furfural analysis	Paper ageing & hotspots	None (integrates over time)	Cheap & easy On-line	Routine
Radio interference	Discharge	None or partial	Cheap & easy on-line	Routine
Acoustic emission	Discharge	Good if discharge not in winding	Moderate cost on-line	Investigation
Infra red emission	Tank currents Cooler blockages	Good	Moderate cost on-line	Routine? Investigation
Frequency Response	Mechanical condition	Partial	Expensive Outage & disconnection required	Investigation
Power Factor	Oil/paper condition	Partial	Expensive Outage & disconnection required	Investigation
Polarisation Spectrum	Paper moisture ageing?	None	Expensive outage required	Investigation Routine at major maintenance?
Winding resistance	Electrical condition	Partial	Expensive Outage required	Investigation

● Equivalent circuits for dielectrics

The purpose of an equivalent diagram of a dielectric is to explain complicated physical relations by means of similar electric conditions.

Most dielectric properties are nonlinear, but normally linear lumped parameters are used in equivalent diagrams.

Equivalent circuits for dielectrics should be used with caution bearing in mind their limitations. Normally they are only valid within a certain range.

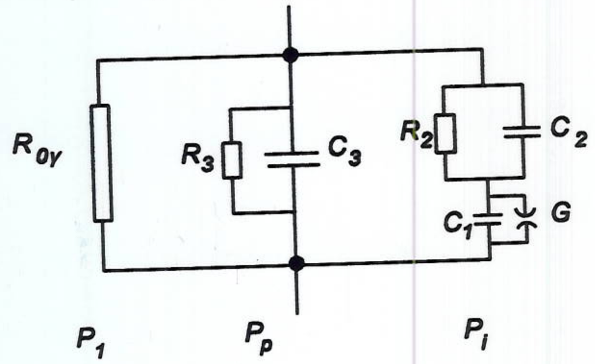


Fig. 9.1 Equivalent scheme for a lossy dielectric
P_1 conductive losses, P_p polarizations losses, P_i ionisation losses

- An ideal dielectric would only comprise the capacitance C_3

- Conductive losses are simulated by means of parallel resistor R_{0Y}

- The polarization losses causes a real component of the capacitive current , which is simulated by means of R_3.

- Partial discharges are modelled with the rigth branch:
  - C_1: partial element which breaks down during PD.
  - G: Gaseous partial discharge.
  - C_2 and R_2: Impedance in series with faulty PD cavity (C_1). through which a renewed charging of C_1 takes place.

● Measurement of DC conductive current

A homogeneous DC electrostatic field with field strength $\bar{E}$ and conductivity $\gamma = 1/\rho$ gives, on the basis of Ohm's law, the following current density

$$\bar{S} = \gamma \bar{E} \qquad [A/m^2]$$

Dielectric losses can be calculated as

$$P'_{diel} = \bar{E}\,\bar{S} = \gamma E^2 \qquad [\cancel{W}] \quad W/m^3$$

The conductivity of liquid and solid dielectrics is mainly caused by ionic conduction and will thereby strongly depend of temperature and impurities, ie. moisture.

Impressing a constant DC-voltage to a dielectric and measuring the current renders the conductive resistance $R_{0\gamma}$.

The conduction is caused by several mechanisms and tend to be dependent of time. Therefore it is mandatory to measure voltage and current according to a time reference ie. 1 minute after impressing the voltage.

Analytical models for γ og ρ as a function of U and I for plain electrode geometries are accessible.

More funny electrode geometries must be calculated by means of numerical methods ie. MATLAB or a FEM software.

● Technical specifications for different dielectrics

Tabelle A 3.3: Eigenschaften von anorganischen Isolierstoffen

Eigenschaft	Einheit	Glas	Glasfaser (E-Glas)	Quarz-Porzellan KER 110.1	Tonerde-Porzellan KER 110.2	Steatit KER 220
Durchschlagsfeldstärke E_d	kV/mm	10...50	–	20...40	20...40	25...40
Durchgangswiderstand ρ	Ω cm	$10^{12}...10^{14}$	10^{13}	10^{12}	10^{12}	10^{12}
Dielektrizitätszahl ϵ_r	–	4,5...7	6	6	6	6
Verlustfaktor (1 MHz) $\tan\delta$	–	$10^{-2}...10^{-3}$	10^{-3}	$5 \cdot 10^{-3}$	$5 \cdot 10^{-3}$	$5 \cdot 10^{-4}$
Kriechstromfestigkeit	–	KA 3c	KA 3c	KA 3c	KA 3c	KA 3c
Dichte γ	g/cm^3	2,2...2,6	2,5	2,3...2,4	2,5...2,6	2,6...2,7
E-Modul	kN/mm^2	60...90	70	50...100	50...100	80...120
Biegefestigkeit	N/mm^2	30...120	–	60...100	100...140	120...150
Zugfestigkeit	N/mm^2	50...100	2500	25...40	40...60	60...90
Druckfestigkeit	N/mm^2	800	–	250...500	400...700	800...1000
Wärmeleitfähigkeit λ	W/K m	0,7...1,1	1,1	1,5...2,5	1,5...2,5	2...4
lineare Wärmedehnung	10^{-6}/K	3...9	5	4...6	4...6	6...9
spezifische Wärme c	J/kg K	700...800	800	800	800	800
Lichtbogenfestigkeit	–	L 6	–	L 6	L 6	L 6

● Measuring setup for the examination of conductive current for dielectrics

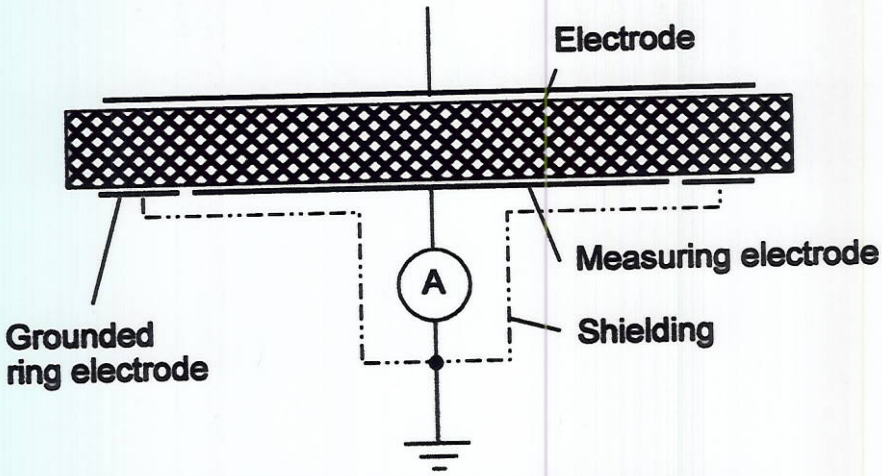


Fig. 9.2 Setup for measurement of DC conductivity of an insulating plate.

- Measuring voltage 100 or 1000 V are connected between top electrode and ground.

- Measuring electrode grounded via highly sensitive ammeter.

- The grounded (protection) ring electrode eliminates the influence of surface leakage current and edge stray field.

- Conductance γ will typically be within the range $10^{-16} < \gamma < 10^{-10}$ S/cm, giving rise to currents in the pA - nA range. Shielding is necessary !!

DC conductance measurements can be used to examine:

- Specific material properties

- Condition of high-capacitance dielectrics. Used to monitor large electrical machines in service (on-line monitoring).

Measurement of AC dielectric loss angle

A dielectric between electrodes connected to 50 Hz AC voltage will posess an electrostatic field E giving rise to a current density of:

$$\bar{S} = (\gamma + j\,\omega\,\tilde{\varepsilon})\,\bar{E} \qquad [A/m^2]$$

Conducting losses determine γ, but polarization losses and ionisation losses will normally also be present to some extent.

This makes the permittivity complex: $\tilde{\varepsilon} = \varepsilon_o\,\tilde{\varepsilon}_r$

- Conductance is modelled by means of γ

- Polarization losses and ionisation losses are modelled by means of a complex permittivity $\vec{\varepsilon} = \varepsilon' + j\varepsilon''$

The dielectric loss factor (dissipation factor) tg δ is defined as the ratio of active current I_w to the reactive current I_{wl}:

$$tg\delta = \frac{I_w}{I_{wl}} = \frac{P_{diel}}{Q}$$

According to their physical nature dielectric losses can be subdivided into 3 (4) cathegories:

- P_l conductive losses
- P_p polarization losses
- P_i ionisation losses
- P_{diel} total losses

$$P_{diel} = P_l + P_p + P_i \qquad [W]$$

Purely (no P_p and P_i) conductive losses gives the following dissipation factor:

$$tg\ \delta_1 = \frac{\gamma}{\omega\ \varepsilon_o\ \varepsilon_r}$$

REMEMBER

$$S = (\gamma + j\omega\varepsilon)E = \underbrace{\gamma E}_{I_w \atop P} + \underbrace{j\omega\varepsilon \cdot E}_{I_{wL} \atop Q}$$

Practical dielectrics containing all 3 loss types (P_l, P_p and P_i) and wil give rise to a current according to:

EFFECTIVE MEASURED RELATIVE PERMITTIVITY.

DEFINITION →

$$i(\omega) = j\omega\varepsilon_0\, \vec{\varepsilon}_r(\omega) E(\omega)$$

The dielectric permittivity is complex and given by:

$$\vec{\varepsilon}_r(\omega) = \varepsilon_r'(\omega) - j\left[\varepsilon_r''(\omega) + \frac{\lambda}{\varepsilon_0\omega}\right]$$

The real part of the above defines the capacitance of the test object while the imaginary represents the losses. Both quantities are frequency dependent.

This gives rise to a generally applicable dissipation factor

$$\tan\delta(\omega) = \frac{\varepsilon_r''(\omega) + \dfrac{\lambda}{\varepsilon_0\omega}}{\varepsilon_r'(\omega)}$$

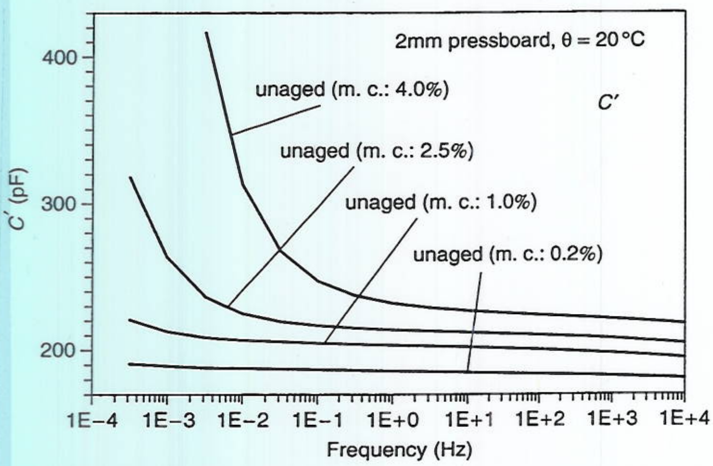


Figure 7.4 *Real part of the complex capacitance of pressboard samples*

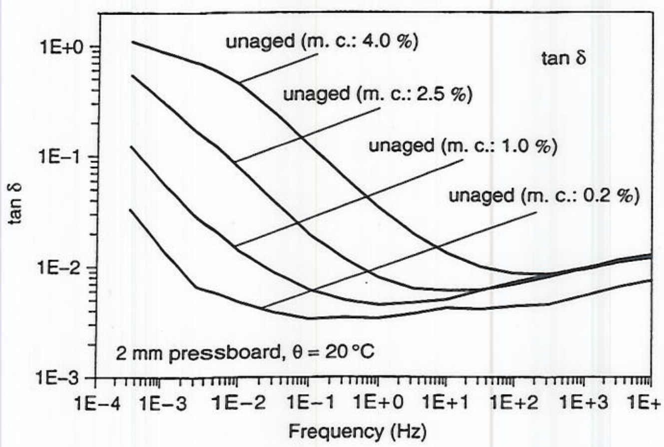


Figure 7.5 *Dissipation factor tan δ of pressboard samples frequency*

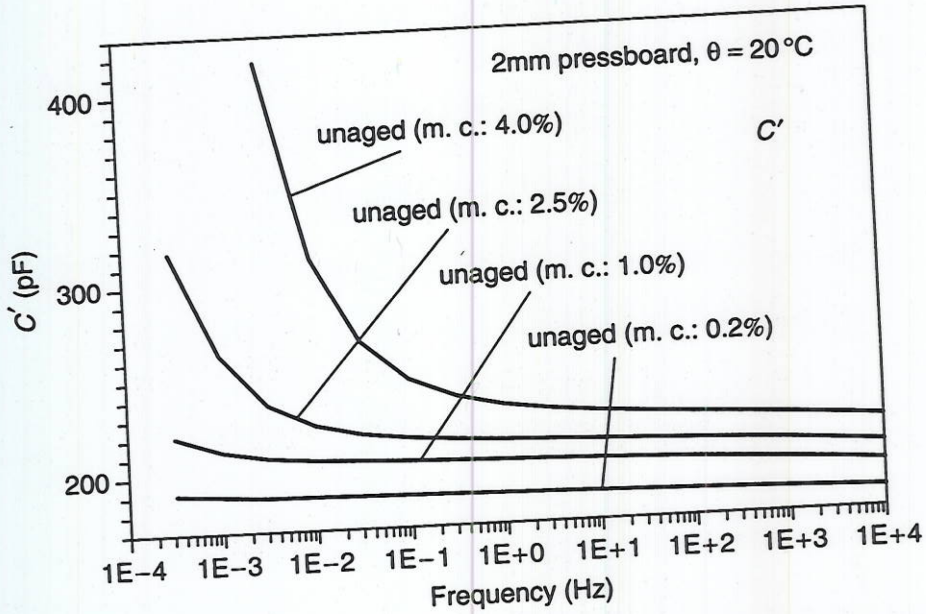


Figure 7.4 *Real part of the complex capacitance of pressboard samples in dependence on frequency*

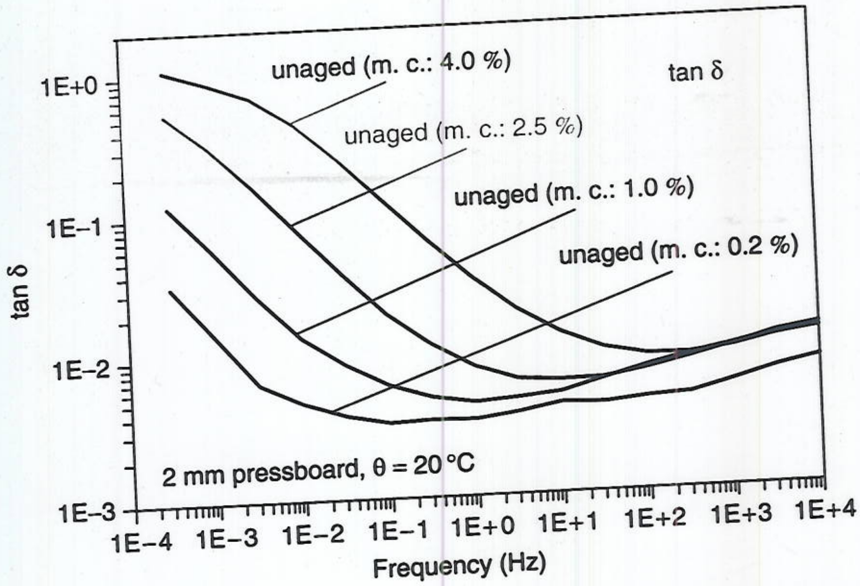
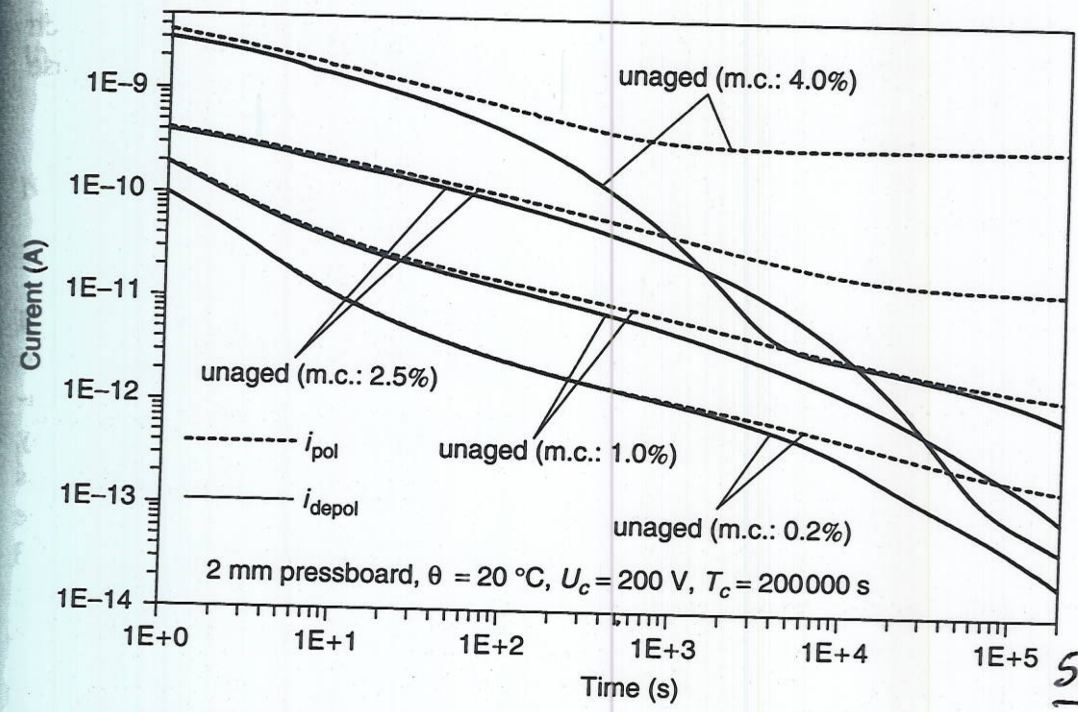


Figure 7.5 *Dissipation factor tan δ of pressboard samples in dependence on frequency*

MOISTURE CONTENT INCREASING ⟹
LOW FREQUENT tan δ INCREASE



56 hours

Figure 7.3 *Relaxation currents of unaged samples with different moisture contents*

OIL - PAPER SAMPLES
MOISTURE CONTENT m.c.

Measurement started 1s after application of Voltage / short circuit.

THE GRAPH SHOWS CLEARLY THAT BOTH $i_{pol}(t)$ AND $i_{depol}(t)$ GIVES THE DIELECTRIC RESPONSE FUNCTION $f(t)$ - AS THEY AGREE UP TO APPR. 10^3 s. AFTER 10^3 s i_{pol} APPROACHES DC CONDUCTIVITY AND i_{depol} ⟶ 0

RECOVERY VOLTAGE

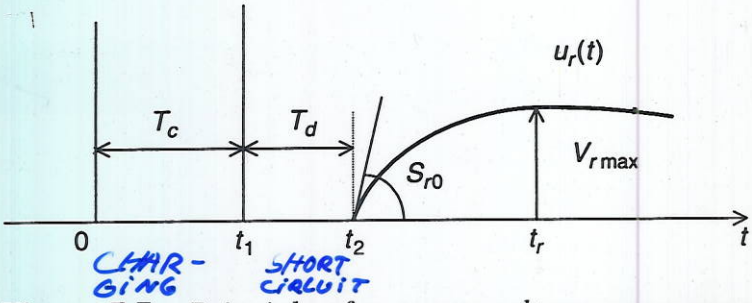


Figure 7.7 *Principle of recovery voltage measurement*

The 'polarization spectrum'

● Calculation of dielectric losses

The losses of a dielectric can be calculated on the basis of (definition)

- The loss angle
- Capacitance
- Voltage
- Frequency

$$P_{diel} = Q \; tg \; \delta = \omega C \; tg(\delta) \; U^2 \qquad [W]$$

Specific dielectric losses P_{diel}' for an infinitesimal volume

$$P_{diel}' = \frac{dP_{diel}}{dV} = E^2 \bullet \omega \bullet \varepsilon_0 \bullet \varepsilon_r \bullet \tan(\delta) \qquad [W/m^3]$$

The E-field strength E = f(x, y, z) is 3-dimensional and will depend on the location in the space between the electrodes.

This makes it necessary to integrate the above equation to calculate the total amount of losses of a dielectric system.

It is much easier to calculate the losses on the basis of the capacitance
$P_{diel} = \omega \; C \; \tan(\delta) \; U^2$

The capacitance can be calculated analytically or by FEM.

● Equivalent circuits for dielectrics

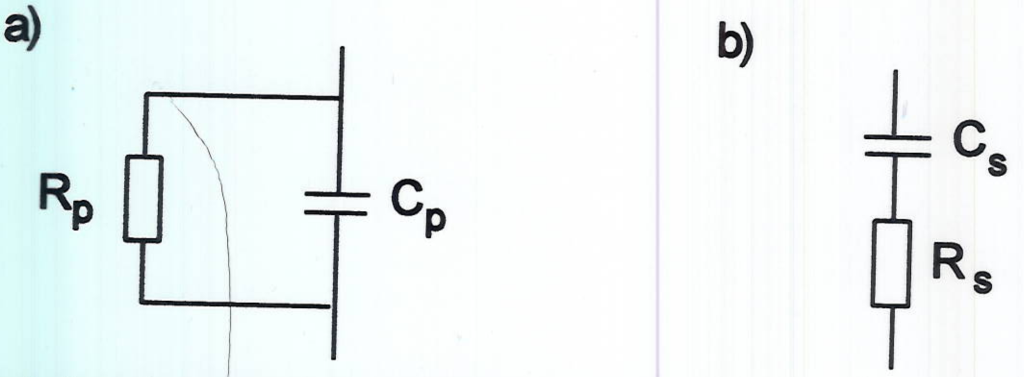


Fig. 9.3 Equivalent scheme for a lossy dielectric at AC voltage
a) parallel, b) series

The loss angle can be calculated on the basis of measurements of the lumped parameters.

<u>Series circuit</u>

$$tg\ \delta_s = R_s\ \omega\ C_s$$

<u>Parallel circuit</u>

$$tg\ \delta_p = \frac{1}{R_p\ \omega\ C_p}$$

CONVERSION

$$C_p = \frac{C_s}{1+(\tan\delta_s)^2}$$

$$R_p = R_s\left(1 + \frac{1}{1+(\tan\delta_s)^2}\right)$$

At fixed frequency both are applicable and can be converted.

The general frequency dependence makes the use of the above equivalent circuits rather limited.

It is possible to extent the equivalent scheme for dielectrics with several lumped paramters depending on frequency a.o. which makes such a semiempirical approach applicable to a wider range.

● Schering-bridge measurements

The Schering bridge was invented by Mr. H. Schering in 1919 for measurement of High Voltage AC dielectric losses.

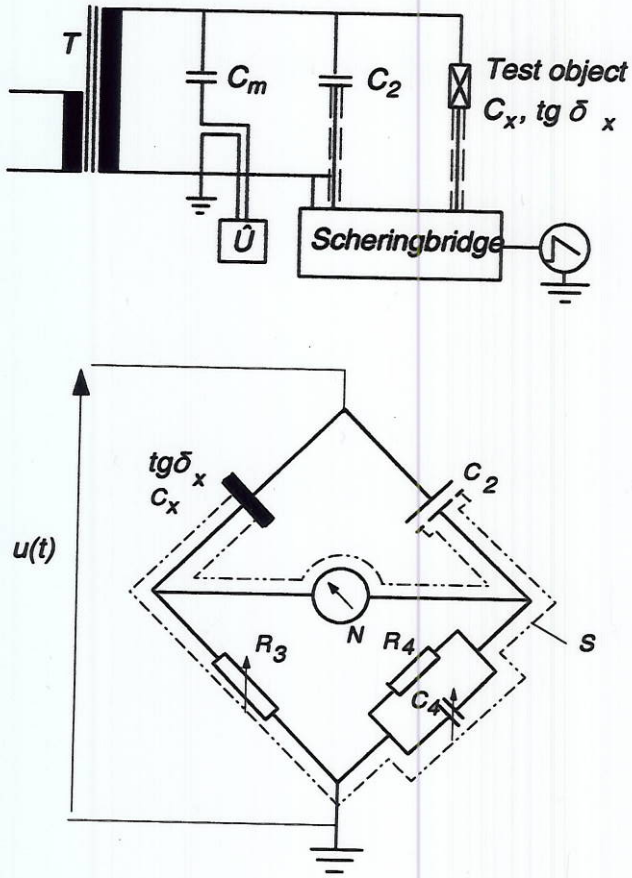
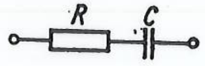
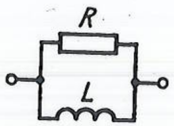
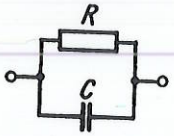
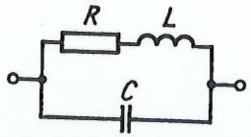
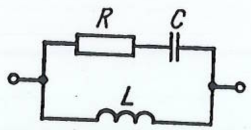


Fig. 9.4 Connection of the Schering bridge for measurement of capacitance and dissipation factor for a HV test object.C_x test object, C_2 normal capacitor, R_3, R_4, C_4 bridge components, N zero balance indicator, S shielding

The bridge contains the adjustable components R_3, R_4 og C_4 placed in a shielded and grounded metal box. Test object C_X and normal capacitor C_2 connected to HV.

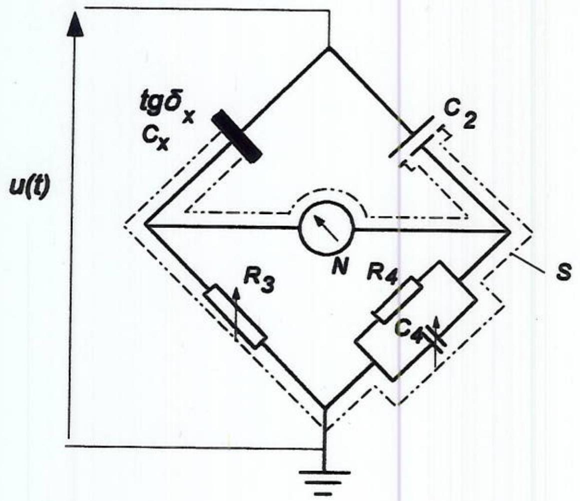
Zero balancing instrument N must **only** be sensitive to the fundamental frequency of the HV test voltage.

Tafel 1.24 Komplexe Widerstände und Leitwerte einfacher Schaltungen

Schaltung	Z	Y	$\tan \varphi_z = -\tan \varphi_y$	$Z = 1/Y$
	$R - \mathrm{j}\dfrac{1}{\omega C}$	$\dfrac{\omega^2 C^2 R}{1 + \omega^2 R^2 C^2} + \mathrm{j}\dfrac{\omega C}{1 + \omega^2 C^2 R^2}$	$-\dfrac{1}{\omega C R}$	$\dfrac{\sqrt{1 + \omega^2 C^2 R^2}}{\omega C}$
	$R + \mathrm{j}\omega L$	$\dfrac{R}{R^2 + \omega^2 L^2} - \mathrm{j}\dfrac{\omega L}{R^2 + \omega^2 L^2}$	$\dfrac{\omega L}{R}$	$\sqrt{R^2 + \omega^2 L^2}$
	$\dfrac{R\omega^2 L^2}{R^2 + \omega^2 L^2} + \mathrm{j}\dfrac{R^2 \omega L}{R^2 + \omega^2 L^2}$	$\dfrac{1}{R} - \mathrm{j}\dfrac{1}{\omega L}$	$\dfrac{R}{\omega L}$	$\dfrac{R\omega L}{\sqrt{R^2 + \omega^2 L^2}}$
	$\dfrac{R}{1 + \omega^2 C^2 R^2} - \mathrm{j}\dfrac{\omega C R^2}{1 + \omega C^2 R^2}$	$\dfrac{1}{R} + \mathrm{j}\omega C$	$-R\omega C$	$\dfrac{R}{\sqrt{1 + \omega^2 C^2 R^2}}$
	$\dfrac{R}{(1 - \omega^2 LC)^2 + \omega^2 C^2 R^2} + \mathrm{j}\dfrac{\omega L - \omega C(R^2 + \omega^2 L^2)}{(1 - \omega^2 LC)^2 + \omega^2 C^2 R^2}$	$\dfrac{R}{R^2 + \omega^2 L^2} - \mathrm{j}\dfrac{\omega L - \omega C(R^2 + \omega^2 L^2)}{R^2 + \omega^2 L^2}$	$\dfrac{\omega L - \omega C(R^2 + \omega^2 L^2)}{R}$	$\dfrac{\sqrt{R^2 + \omega^2 L^2}}{\sqrt{(1 - \omega^2 LC)^2 + \omega^2 C^2 R^2}}$
	$\dfrac{R\omega^2 L^2 \omega^2 C^2}{(1 - \omega^2 LC)^2 + \omega^2 C^2 R^2} + \mathrm{j}\dfrac{\omega L(1 - \omega^2 LC + R^2 \omega^2 C^2)}{(1 - \omega^2 LC)^2 + \omega^2 C^2 R^2}$	$\dfrac{R\omega^2 C^2}{1 + \omega^2 C^2 R^2} - \mathrm{j}\dfrac{1 - \omega^2 LC + \omega^2 C^2 R^2}{\omega L(1 + \omega^2 C^2 R^2)}$	$\dfrac{1 - \omega^2 LC + \omega^2 C^2 R^2}{R\omega L \omega^2 C^2}$	$\dfrac{\omega L\sqrt{1 + \omega^2 C^2 R^2}}{\sqrt{(1 - \omega^2 LC)^2 + \omega^2 C^2 R^2}}$

RLC-Reihen- bzw. Parallelschaltung s. S. 130 und S. 131

● **Schering-bridge balanced ➔ determination of C_X and tan δ_X**



Balancing the bridge makes no current in the middle branch and thereby the voltage zero. Voltage division gives:

$$U_{left\ corner} = U\frac{Z_X}{Z_X + Z_3} \quad and \quad U_{right\ corner} = U\frac{Z_2}{Z_2 + Z_4}$$

This makes

$$U_{diagonal} = U\left(\frac{Z_X Z_4 - Z_2 Z_3}{(Z_X + Z_3)(Z_2 + Z_4)}\right)$$

Diagonal voltage becomes zero for the following conditions

$$Z_X Z_4 = Z_2 Z_3 \quad or \quad Y_X Y_4 = Y_2 Y_3$$

This implies that the following must be valid

$$|Z_X| \bullet |Z_4| = |Z_2| \bullet |Z_3| \quad and \quad \varphi_X + \varphi_4 = \varphi_2 + \varphi_3$$

The following apply to the Schering bridge

- $\varphi_2 = 90°$ because Z_2 is purely capacitive
- $\varphi_3 = 0°$ because Z_3 is purely resistive

This makes $\varphi_4 = 90° - \varphi_X$ and the loss angle δ is complementary to φ ➔ $\delta_x = 90° - \varphi_x$, which adds up to

$$\varphi_4 = 90° - \varphi_X = \delta_X$$

$$\tan \varphi_{PAR} = \frac{R}{X} = \frac{R}{\frac{1}{\omega C}} = R\omega C$$

The adjustable impedance Z_4 is a parallel connection so

$$\boxed{\tan(\varphi_4) = \omega \bullet R_4 \bullet C_4 = \tan(\delta_X)}$$

Capacitance of the test object is

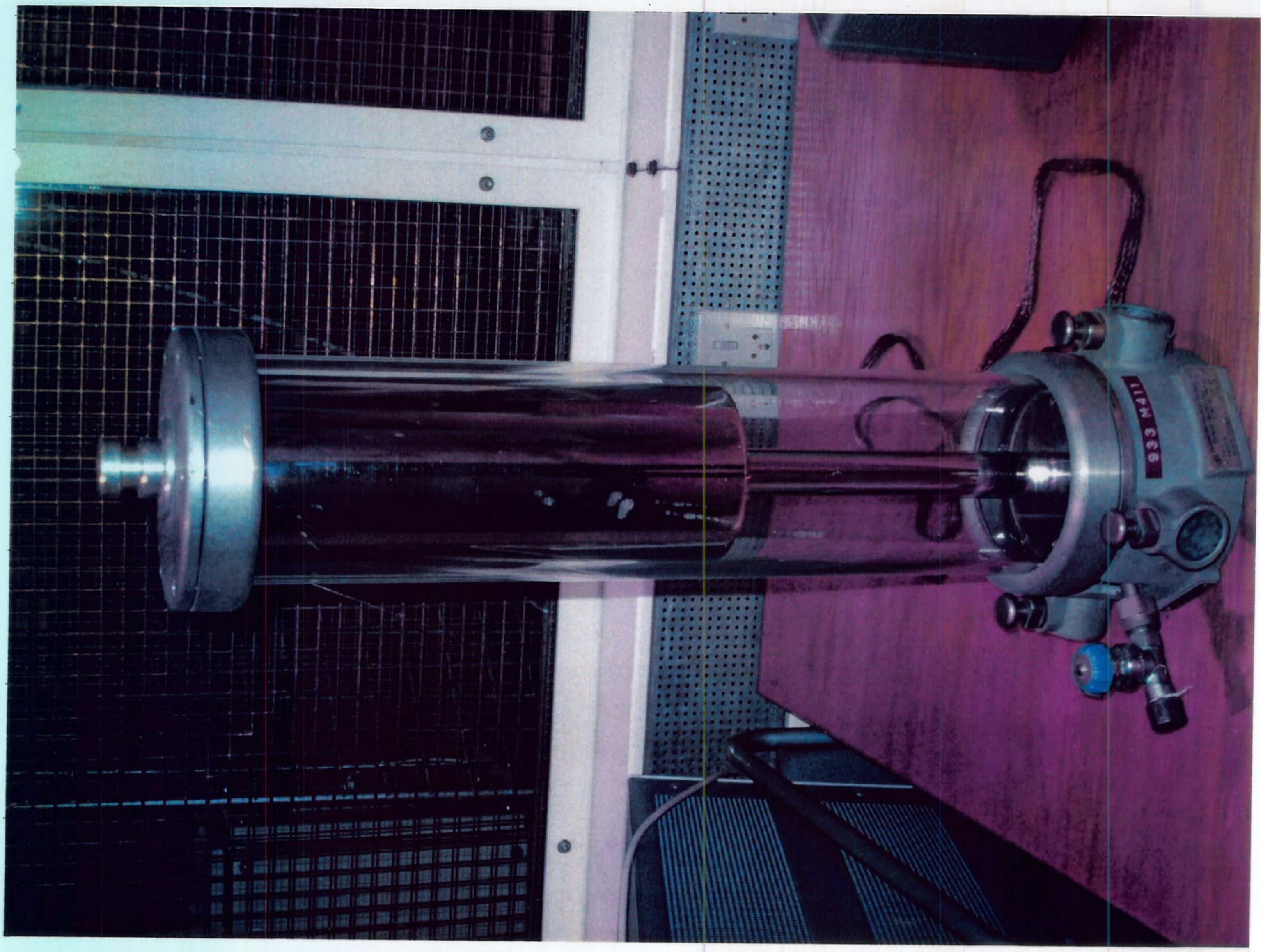
$$\boxed{C_x = C_2 \frac{R_4}{R_3(1 + tg^2\delta_x)} \simeq C_2 \frac{R_4}{R_3} \quad [F]}$$

● Normal capacitor for Schering bridge measurements

The applied normal capacitor C_2 har to be a very high quality component. The bridge determination is based on assuming $\varphi_2 = 0$.

Pressurized gas capacitors has a very constant capacitance which is unaffected by surrounding pressure and temperature.

Besides that almost no partial discharges occur in a pressurized gas capacitor.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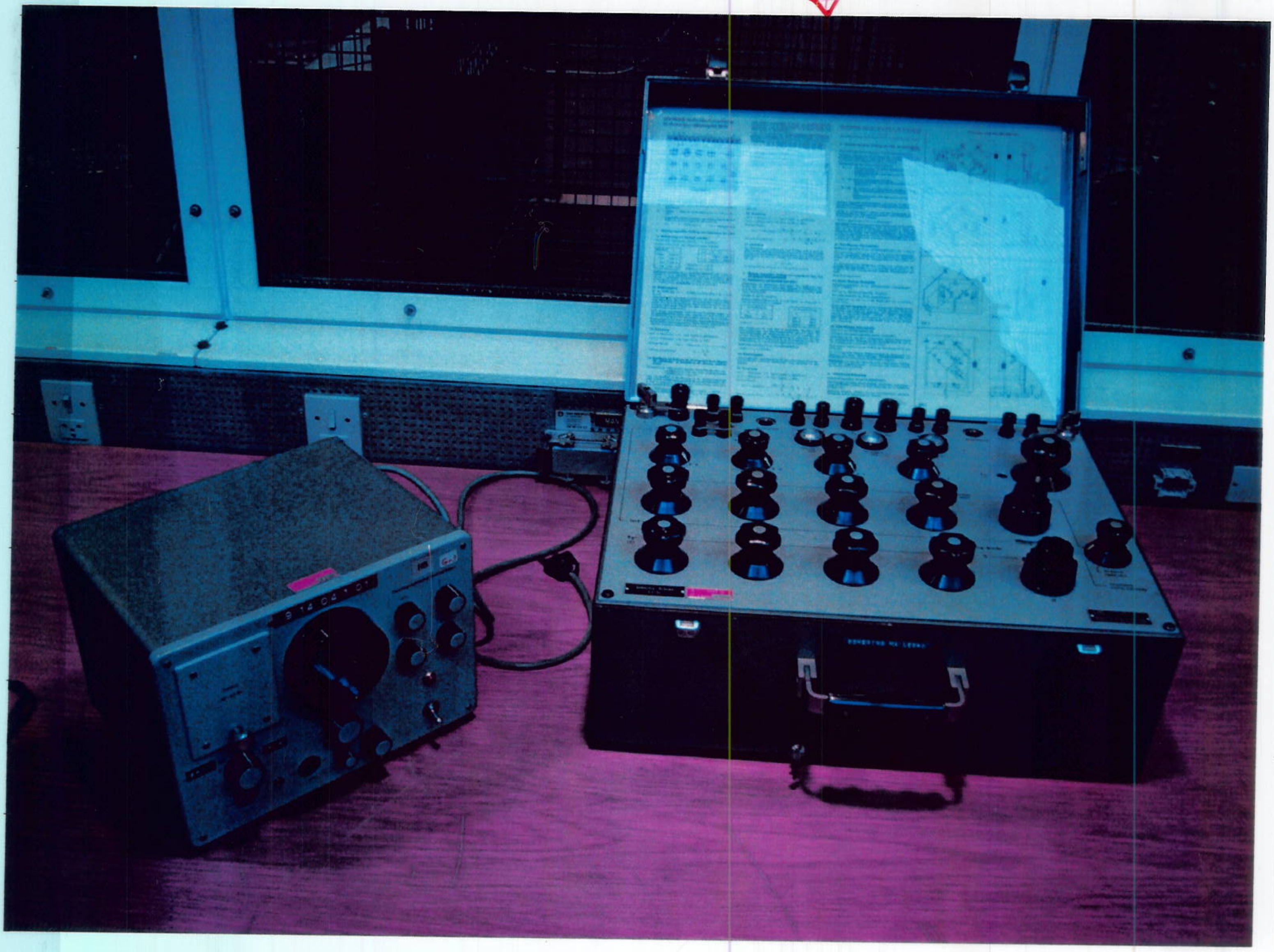
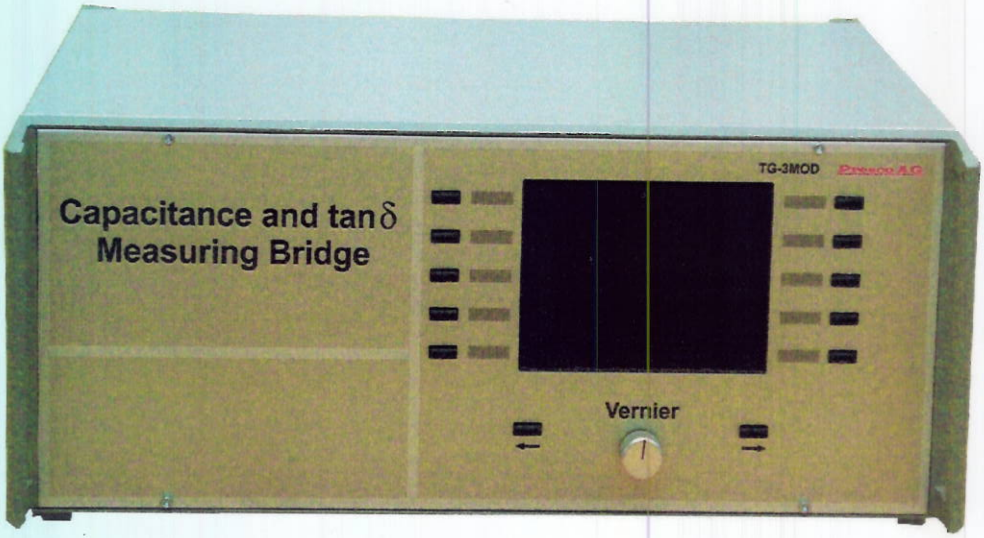


Capacitance and Dissipation Factor Measuring Bridge TG-3MOD



- 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

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