High Voltage Testing

HV Test Laboratories

- Voltage levels of transmission systems increase with the rise of transmitted power.
- Long-distance transmissions are often arranged by HVDC systems. However, a vast majority of transmission systems is still ensured by AC links.
- The purpose of HV test labs is to verify whether the insulation system can withstand the prescribed stresses.

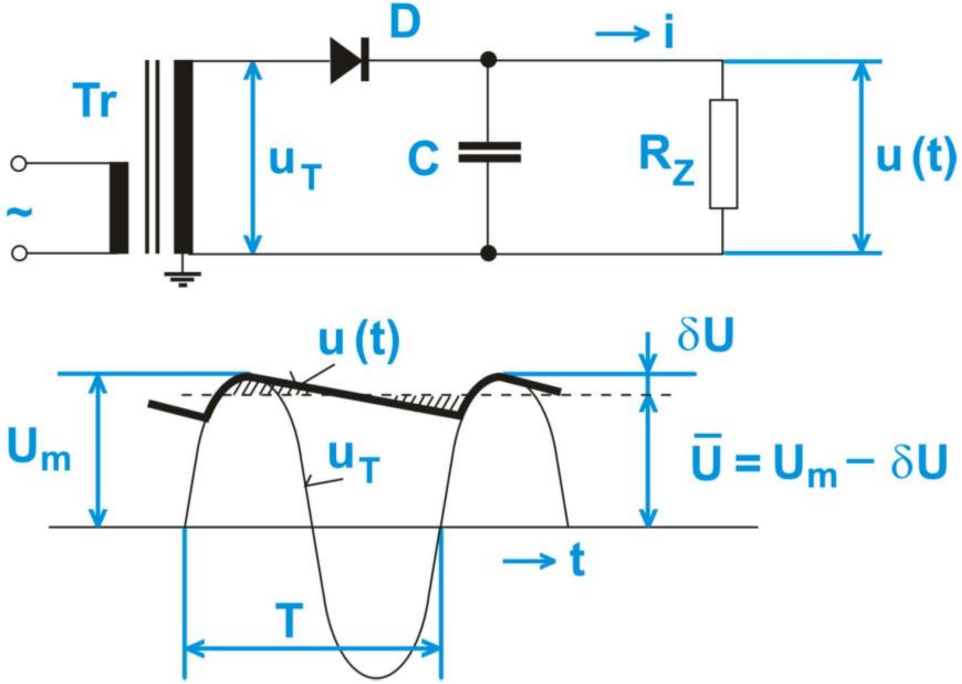
HV Test Laboratories

- The insulation system is subjected to different types of electrical stress during the tests. These tests are:
  - Power frequency voltage withstand test
  - Lightning impulse voltage withstand test
  - Switching impulse voltage withstand test
- The amplitude of voltage and the form of voltage stress depend on both type and rated voltage of a tested machine.

HV Test Laboratories

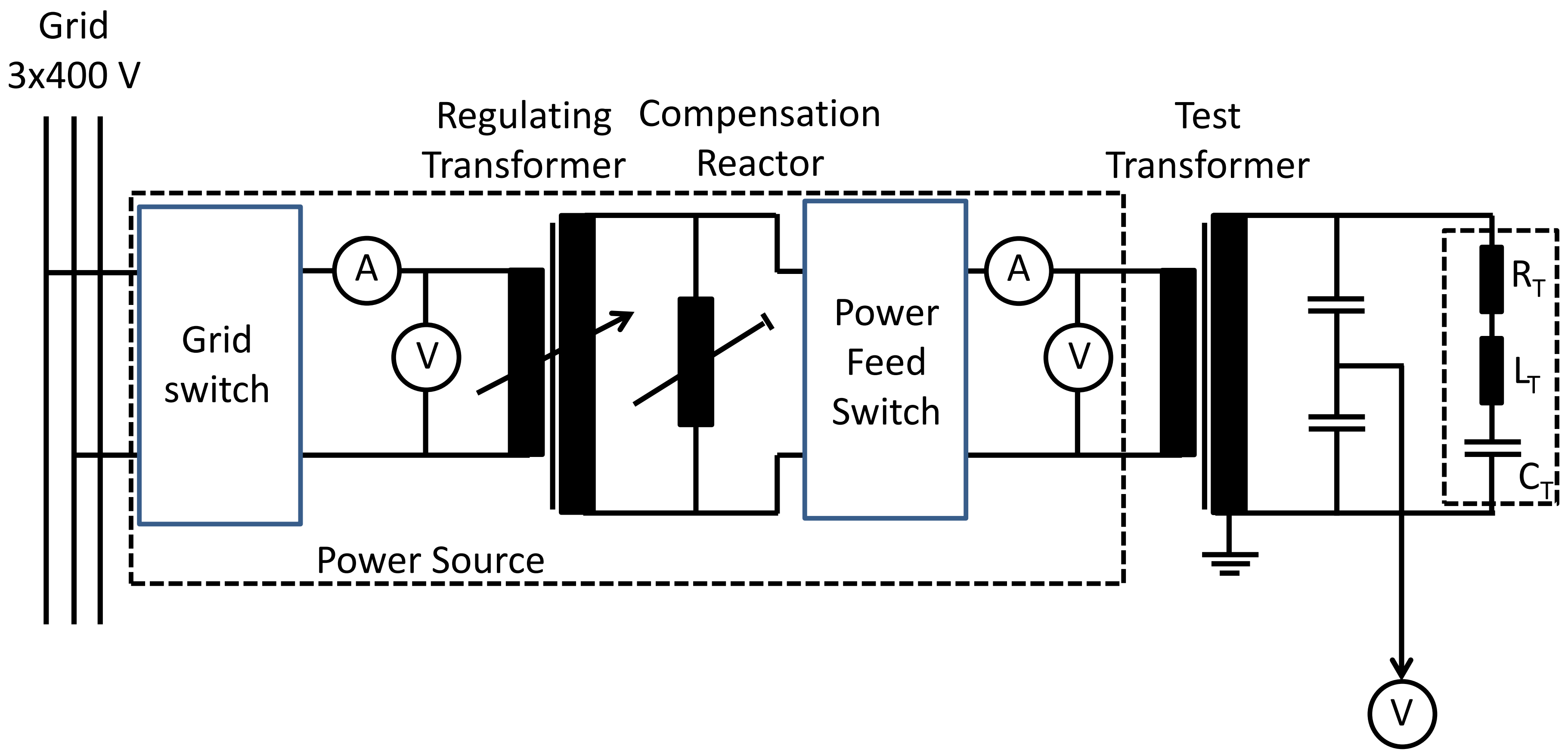
- HV laboratories need to be equipped with relevant high voltage sources:
  - High voltage DC power source
  - High voltage AC power source
  - High voltage impulse power source

DC High Voltage Power Sources



- Ripples (ripple factor) decrease as load R_Z, capacity C or frequency of the voltage increase

AC High Voltage Power Sources



AC High Voltage Power Sources

Test Transformer with Grounded Metallic Tank

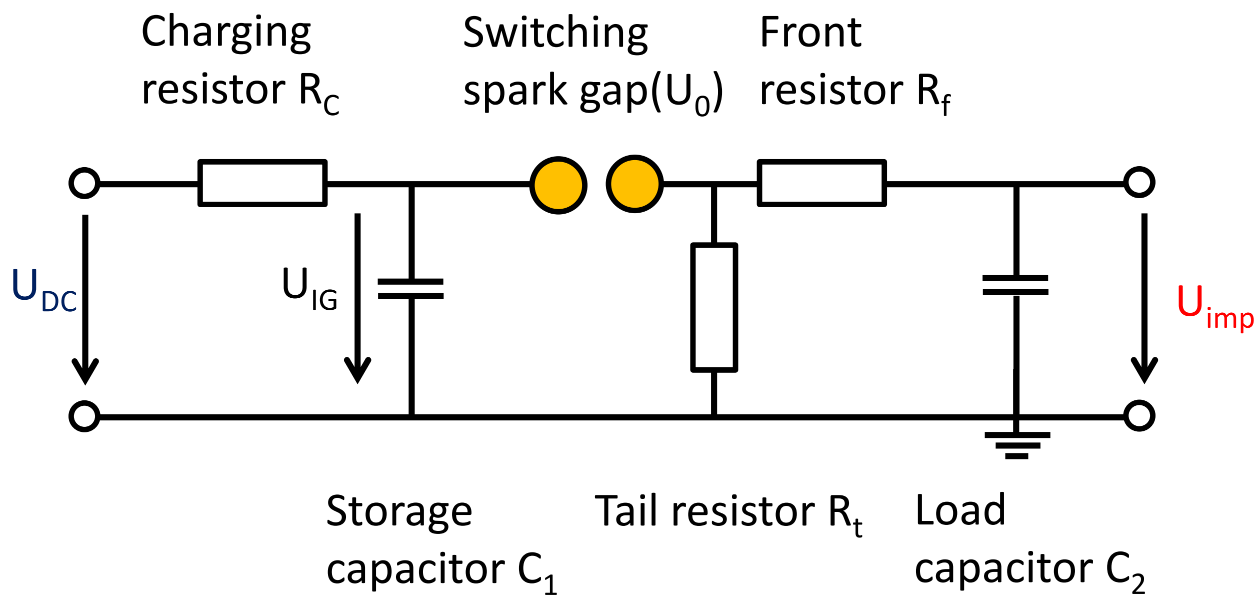
- Better cooling conditions (can be equipped with radiators)
- Since the tank is grounded, the transformer can be placed next to other objects or walls.
- Viable construction for outdoor tests

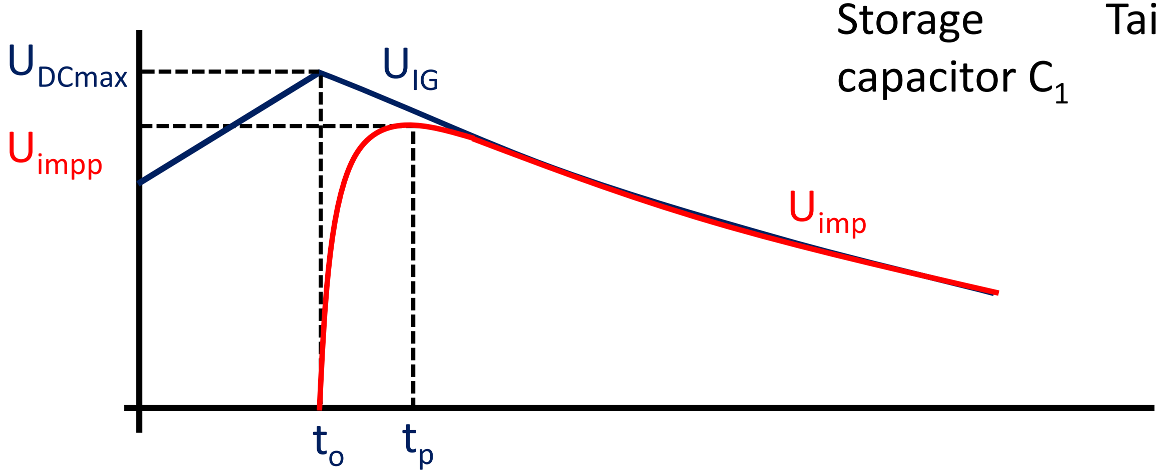
Test Transformer with Insulated Cylindrical Tank

- Does not require a bushing (the surface is insulated)
- Viable for employment as cascade transformers (up to 1500 MVA)
- Only usable indoors for short duration tests

Impulse High Voltage Power Sources

Single stage impulse generator



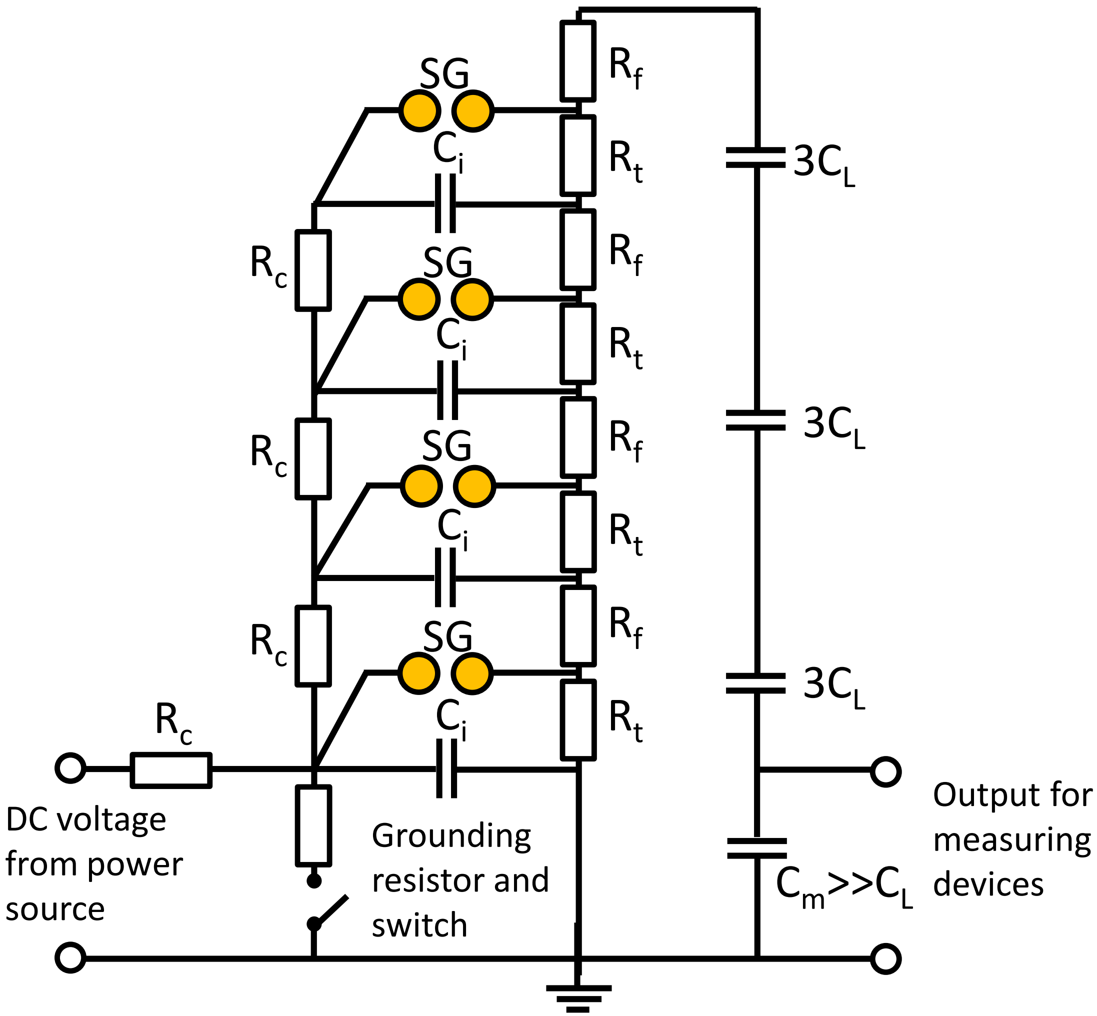


Impulse generator utilization factor

$$\eta = \frac{U_{impp}}{U_{DCmax}} < 1$$

Impulse High Voltage Power Sources

Multistage impulse generator

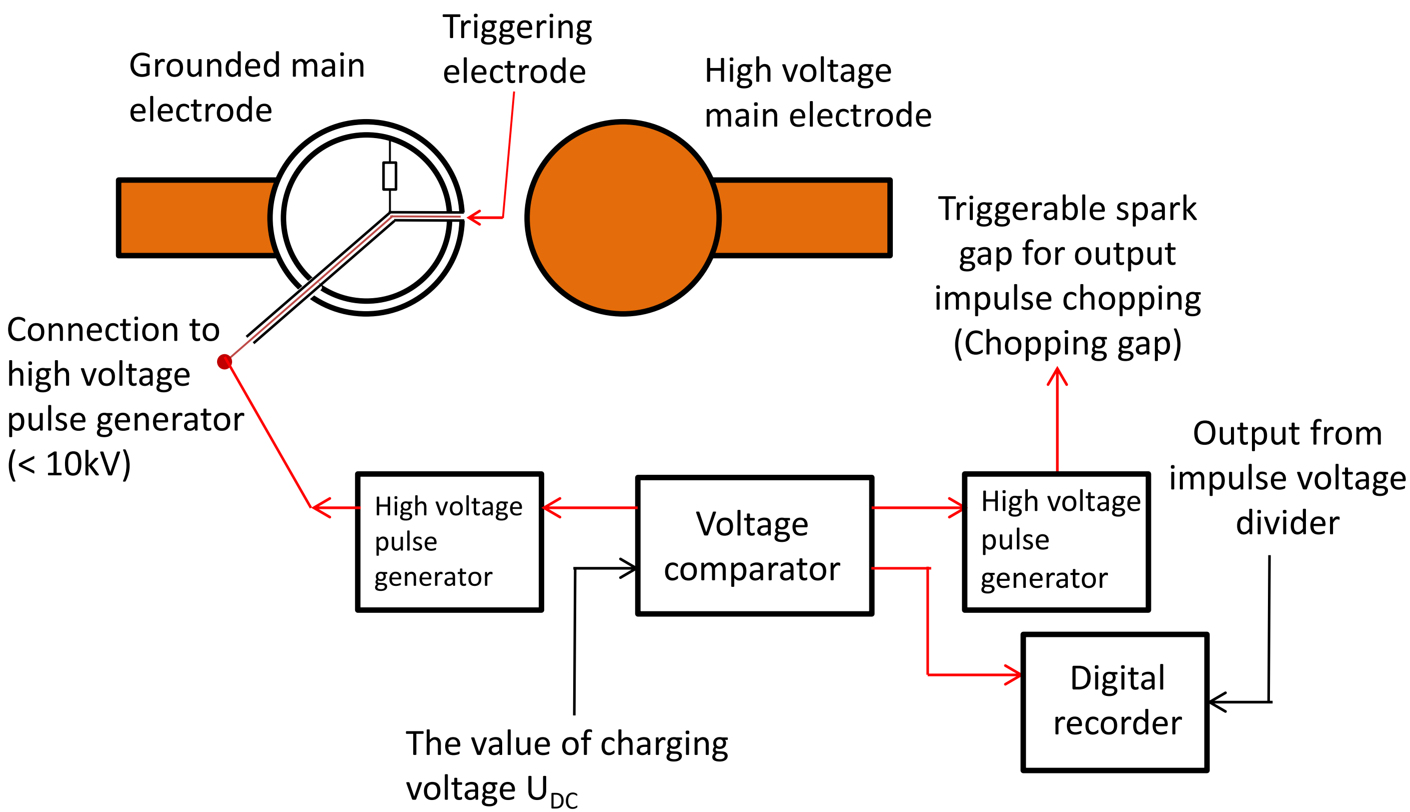


SGSA Impulse Generator Haefely Hipotronics

Output voltage U_{imp} for an n-stage impulse generator with utilization factor η and source voltage U_0:

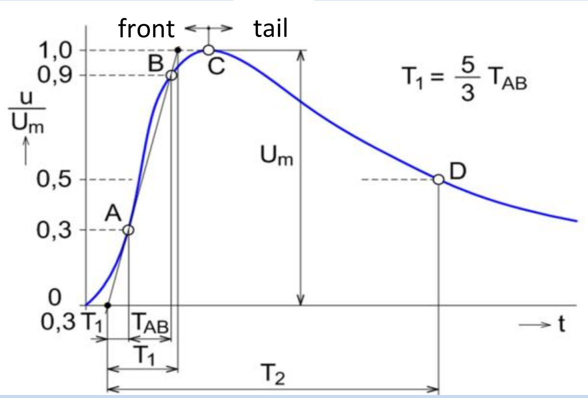
$$U_{imp} = n\eta U_0$$

Impulse Generator Triggering (Trigatron)



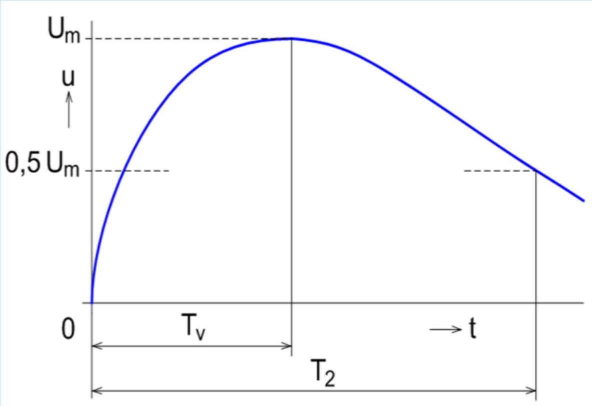
Output Voltage of Impulse Generator

Lightning impulse



- The polarity and peak voltage of impulse U_m is determined from relevant standard for rated voltage of the tested machine
- Engineering tolerance of peak voltage is 3 %
- Front time T_1=1,2 µs ± 30%
- Tail time T_2=50 µs ± 20%

Switching impulse



- The polarity and peak voltage of impulse U_m is determined from relevant standard for rated voltage of the tested machine
- Engineering tolerance of peak voltage is 3 %
- Front time T_v=250 µs ± 20 %
- Tail time T_2=2500 µs ± 60 %

High Voltage Dividers

- Resistive, capacitive, inductive and combined high voltage dividers are used for high voltage measurements.
- Inductive dividers are primarily employed for calibration purposes as they are far too expensive for very high voltage measurements.
- The upper electrode of a divider is equipped with toroidal rings, which prevent generation of partial discharges.
- The current passing through the divider should be lower than 10 mA (from Ohm‘s law we can determine minimal resistance: 1 MΩ/10 kV)

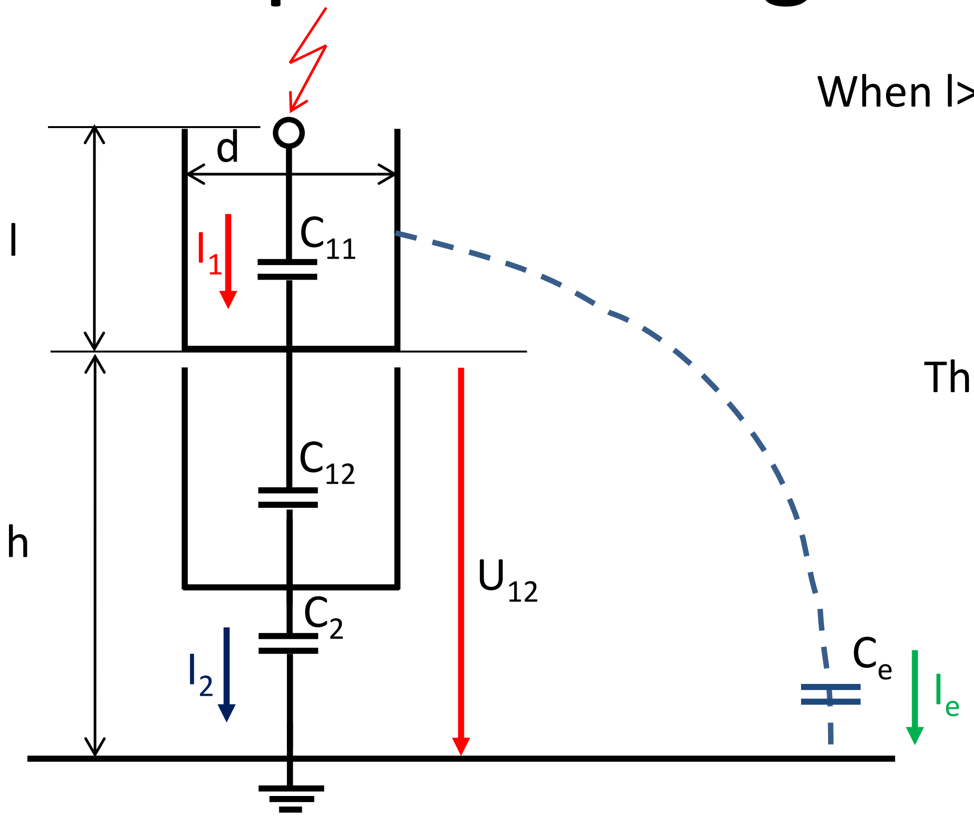
Capacitive High Voltage Dividers

- Primarily used for AC high voltage measurements
- The high voltage part of the divider usually consists of several capacitors.
- The measured voltage U_1 (HV) can be derived from output voltage U_2 as:

$$U_1 = U_2\left(1 + \frac{C_2}{C_1}\right)$$

- In practice, we must consider the effect of parasitic capacitances between the divider‘s cylinder and ground. Therefore, the previous relation must be modified.

Capacitive High Voltage Dividers



When l>>d, C_e can be expressed approximately as:

$$C_e = \frac{2\pi\varepsilon l}{ln\left\{\frac{2l}{d}\sqrt{\frac{4h+l}{4h+3l}}\right\}}$$

The current flowing through C_{12} and C_2 is:

$$I_2 = \omega U_{12} C_{12}$$

The current flowing through parasitic capacitance C_e between shielding of the upper electrode and ground is:

$$I_e = \omega U_{12} C_e$$

By summing up both currents, we can calculate the total current flowing through the upper HV capacitor:

$$I_1 = I_{12} + I_e$$

Voltage drop on the upper capacitor is then:

$$U_{11} = \frac{I_{11}}{\omega C_{11}}$$

Capacitive High Voltage Dividers

Capacitance C_e reduces the total capacity of the HV part of the divider. This effect is magnified with increasing number of employed capacitors.
Effective capacity C_1 of the HV part of the divider that consists of n capacitors of capacity C_{1n} can be expressed approximately as:

$$C_1 \approx \frac{C_{1n}}{n} - \frac{nC_e}{6}$$

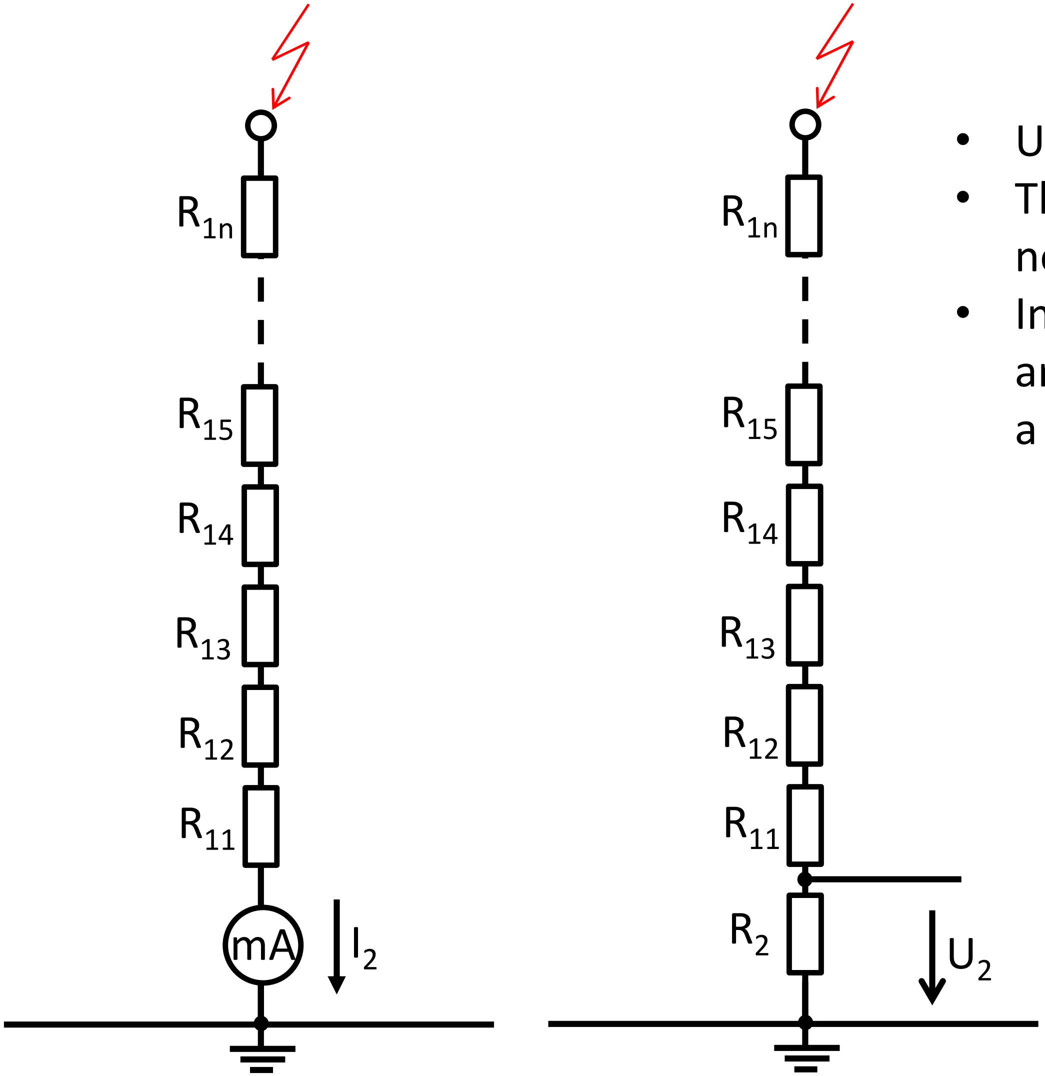
It was experimentally proven that capacity C_e of each capacitor is almost independent on its distance from ground. Therefore, we can utilize the simplified relation:

$$C_e = \frac{2\pi\varepsilon l}{ln\left(\frac{2l}{d}\right)}$$

Hence

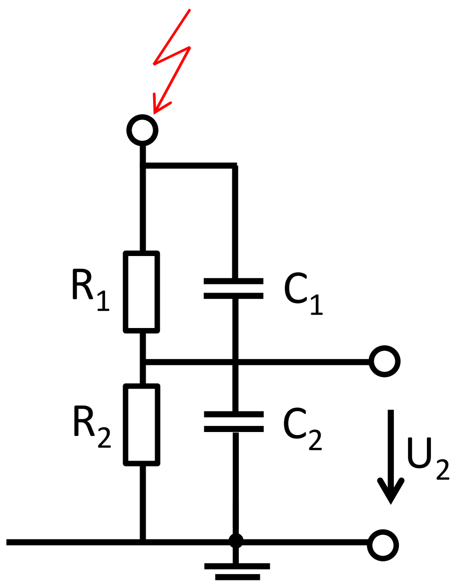
$$C_1 \approx \frac{C_{1n}}{n} - \frac{n\pi\varepsilon l}{3ln\left(\frac{2l}{d}\right)}$$

Resistive High Voltage Dividers

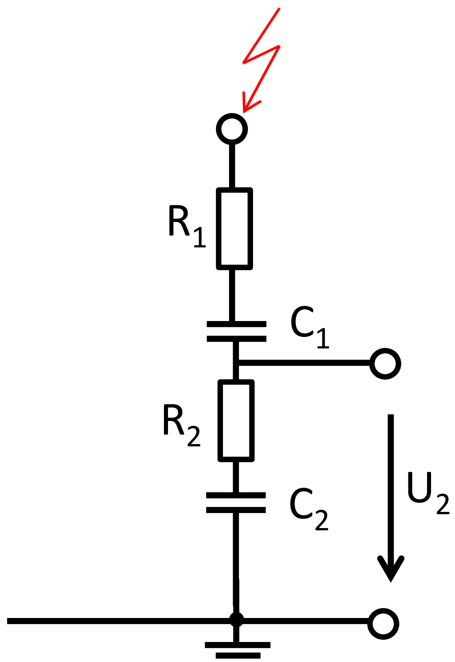


- Used for DC or impulse measurements
- The current through the divider should not exceed 5 mA
- Individual resistors are wrapped around the insulation cylinder to form a helix

RC High Voltage Divider



Parallel combination



Series combination

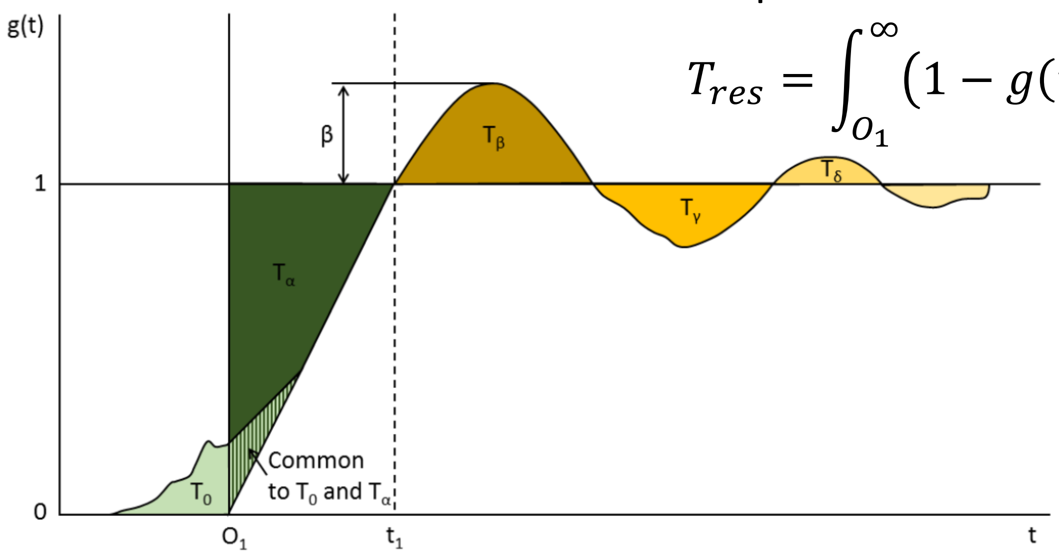
- Parallel combination is used for AC, DC or impulse measurements, series combination is used only for AC or impulse measurements

Dynamic Behavior of HV Dividers

- In the case of lightning impulse voltage tests, it is necessary to verify that the dynamic behavior of a divider meets frequency range requirements. This is particularly important for impulses that are chopped in the tail part.
- Dynamic response of a divider to a unit step voltage is tested by a generator with rise time of units of ns and amplitude of hundreds of volts.

Response time of a divider:

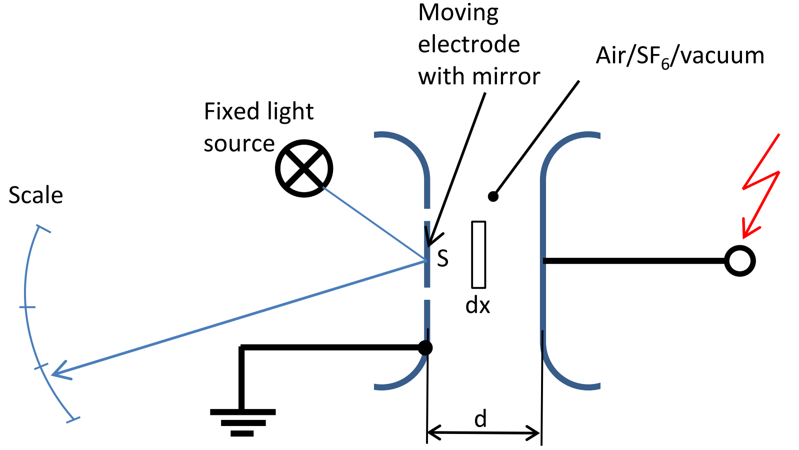
$$T_{res} = \int_{O_1}^{\infty} \big(1 - g(t)\big) dt = T_\alpha - T_\beta + T_\gamma - \cdots$$



Normalized response of a divider to a unit step

Electrostatic Voltmeter

- Direct method of high voltage AC and DC measurement
- Electrostatic voltmeters can be directly connected to HV circuits of voltages up to 200 kV. Should the voltage be any higher, voltage dividers must be employed.



Electric field energy density between electrodes:

$$w_e = \frac{1}{2}\varepsilon E^2$$

Energy density in element Sdx:

$$dw = w_e S dx = \frac{1}{2}\varepsilon S E^2 dx$$

The force acting on the moving electrode:

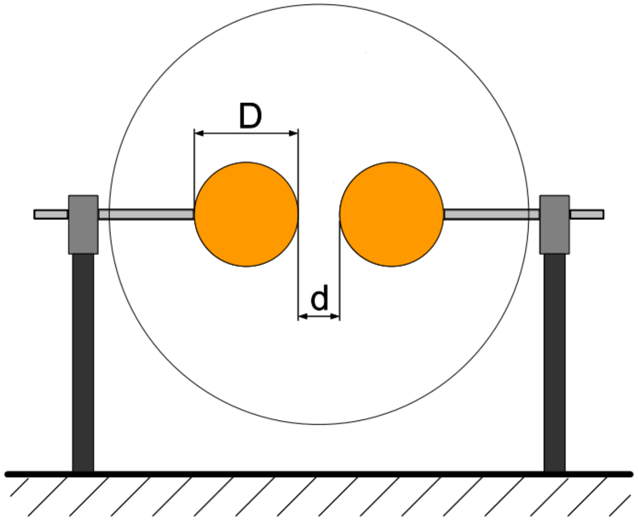
$$F = \frac{dw}{dx} = \frac{1}{2}\varepsilon S E^2 = \frac{1}{2}\varepsilon S \frac{U^2}{d^2}$$

Mean value of force of time variable voltage

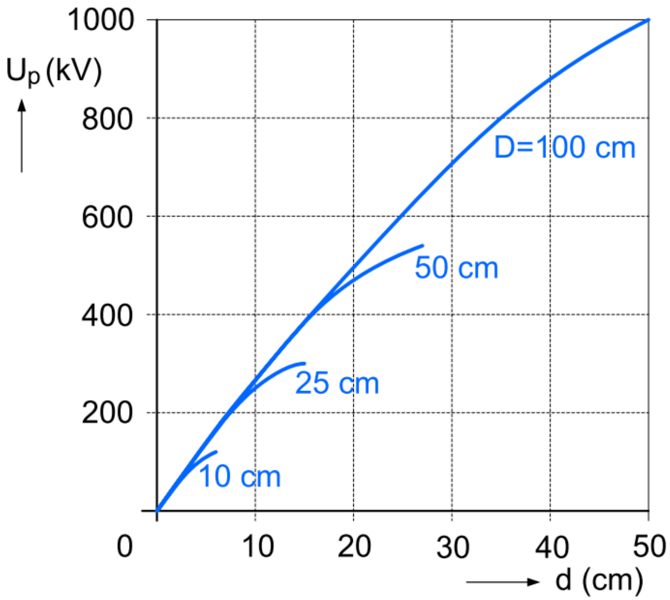
$$\frac{1}{T}\int_0^T F(t)dt = \frac{\varepsilon S}{2d^2 T}\int_0^T U^2(t) = \frac{\varepsilon S}{2d^2} U_{RMS}^2$$

Spark Gaps

- Breakdown voltage in homogeneous or almost homogeneous electric field, such as between two sphere gaps in air, shows high stability and small deviation. Therefore, arrangements with homogeneous fields can be employed for peak voltage measurement.
- Nowadays, sphere gaps are not used for measurements on a daily basis. However, they are sometimes utilized for automatic measurement systems certification or linearity tests.



Dependence of breakdown voltage on electrode distance *d* for different electrode diameters *D*



Adjustment to Actual Atmospheric Conditions

- The value of breakdown voltage measured on sphere gaps is determined from a table of normal atmospheric breakdown voltages. The results have to be adjusted to actual atmospheric conditions.
- Normal atmospheric conditions
  - Normal temperature t_N = 20 °C
  - Normal pressure p_N = 101,3 kPa
  - Normal absolute humidity g_N = 11 g/m^3
- Air density

$$\delta = \frac{t_N + 273}{t_a + 273} \cdot \frac{p_a}{p_N}$$

- The real measured voltage U_s can be calculated from table value U_n as:

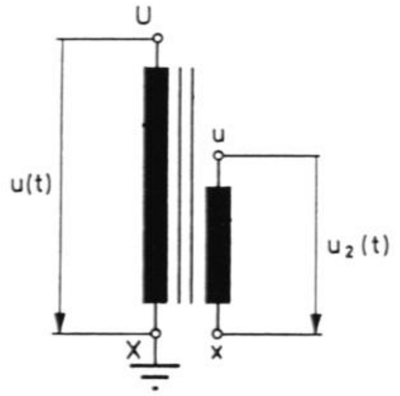
$$U_S = U_N \frac{k_h}{k_v} = U_N \delta$$

- Where $k_h = \delta$ for $0{,}95 < \delta < 1{,}05$ and $k_v = 1$

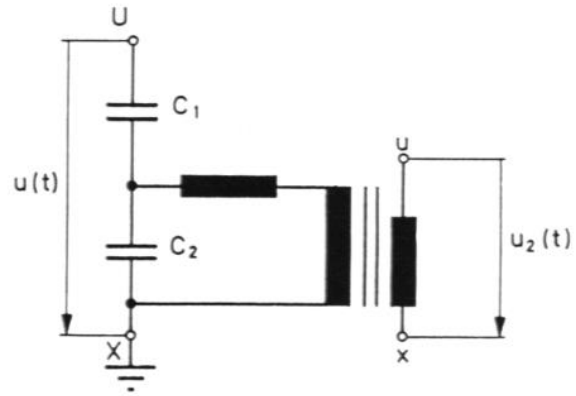
Instrument Voltage Transformers

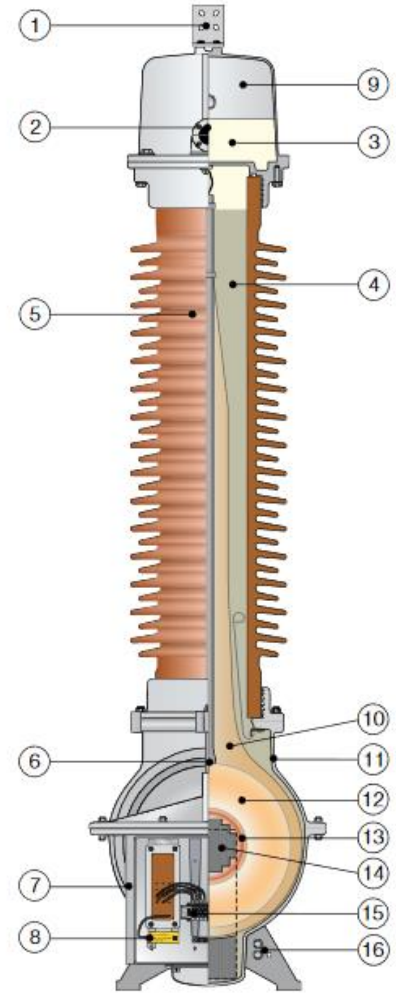
- A special kind of transformers designed to transform high voltage to low voltage (usually 100 V) with prescribed accuracy
- Either inductive (<145 kV) or capacitive (>145 kV) construction.

Inductive instrument transformer



Capacitive instrument transformer





1 – Primary terminal
2 – Oil level sight glass
3 – Oil
4 – Quartz filling
5 – Insulator
6 – Lifting lug
7 – Secondary terminal box
8 – Neutral end terminal
9 – Expansion system
10 – Paper insulation
11 – Tank
12 – Primary winding
13 – Secondary windings
14 – Core
15 – Secondary terminals
16 – Ground connection

ABB, Buyer's guide