Aalto-yliopisto
Sähkötekniikan
korkeakoulu

High Voltage Engineering

Lecture 8: Insulation coordination, Testing and Diagnostics

Mahdi Pourakbari Kasmaei, 2020

Outline

- Insulation coordination
  - Surge arrestors
  - Spark gaps
- Testing
  - Purpose, types, requirements, standards
- Test voltages
  - Standard AC, DC, SI, LI
- Testing vs. Diagnostics
  - Setup and components
  - Voltage dividers
  - Current measurements

Overvoltage Protection

Protection levels:

1. **Avoid direct impact** of overvoltage by directing it towards designated routes *(lightning conductors, shield wires, and Faraday cages)*
2. **Ensure basic impulse level** BIL (withstand level) is not exceeded using HV protection elements:

Surge Arrester

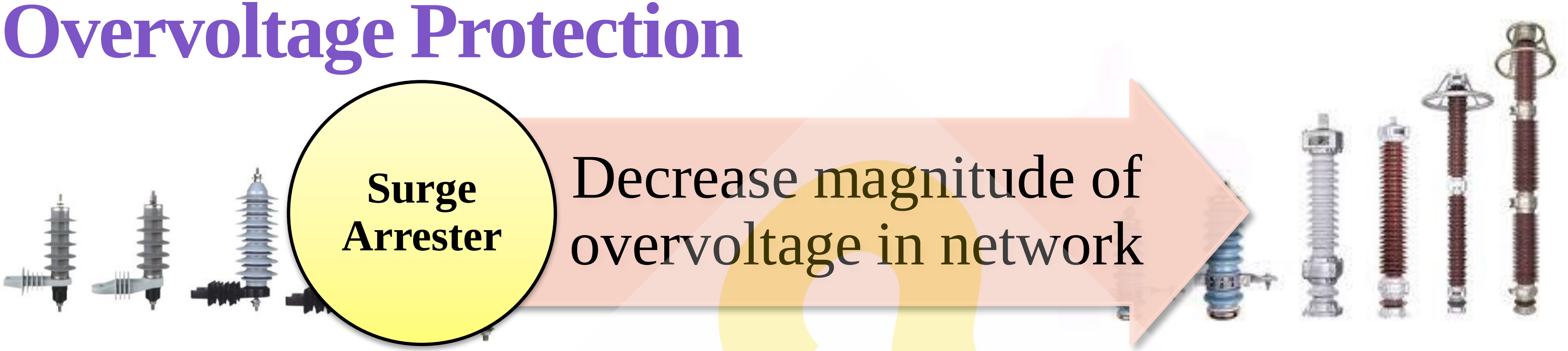
Spark Gap

3. **Extra protection** for sensitive equipment *(LV filters for computers and telecommunication)*

Surge Arresters

- Spark Gap with Non-linear Resistor
  - Magnetic Blow-out Arrester
    - Metal-Oxide Varistor

Overvoltage Protection

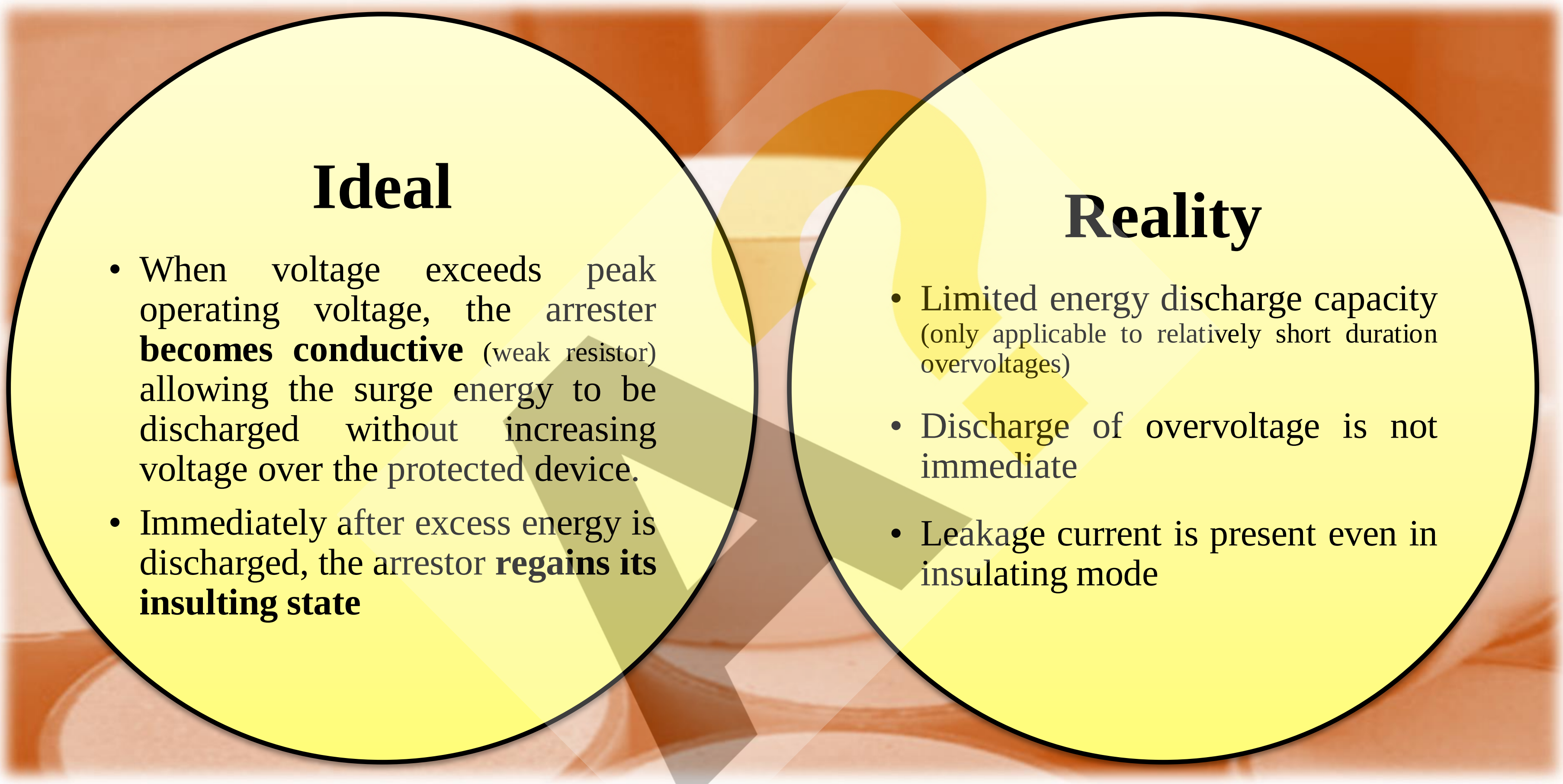


Surge Arrester

Decrease magnitude of overvoltage in network

- ⇨ Traditionally located at substation
    - Protects only **most important equipment** – transformers, GIS
        - used in areas (FIN) where lightning density is low (intensified protection not necessary)
    - Placed at all incoming lines to substation on line-side of feeder circuit breaker
        - all equipment has some level of protection
        - *protection level decreases with distance* between surge arrestor and protected device
- ⇨ Also located at poles
    - Decrease back flashover in areas of high lightning density and poor earthing conditions (not economically feasible in Finland)

Nonlinear Resistance Type Arrester



Ideal

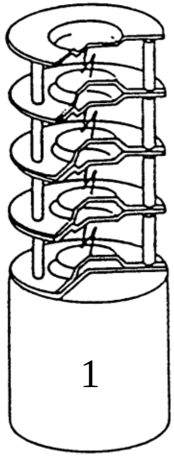
- When voltage exceeds peak operating voltage, the arrester **becomes conductive** (weak resistor) allowing the surge energy to be discharged without increasing voltage over the protected device.
- Immediately after excess energy is discharged, the arrestor **regains its insulting state**

Reality

- Limited energy discharge capacity (only applicable to relatively short duration overvoltages)
- Discharge of overvoltage is not immediate
- Leakage current is present even in insulating mode

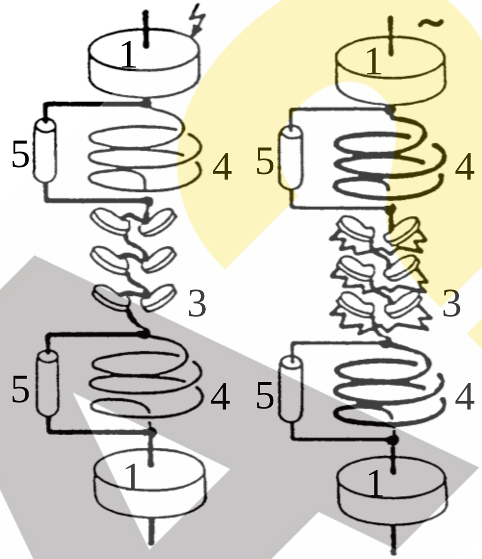
Nonlinear Resistance Type Arrester

1. Nonlinear resistor, **2.** Disc spark gap, **3.** Active spark gap, **4.** Blow-out coil, **5.** Shunting resistor



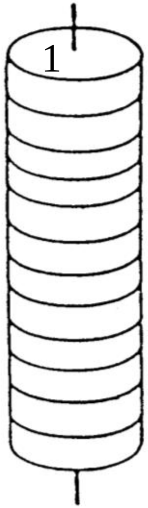
Disk Spark Gap with Nonlinear Resistor

(silicone-carbide gap type)



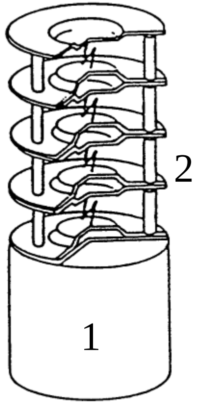
Magnetic Blow-Out Arrester

(active gap surge arrestor, expulsion type)



Metal-Oxide Varistor

Nonlinear resistor Type with gaps



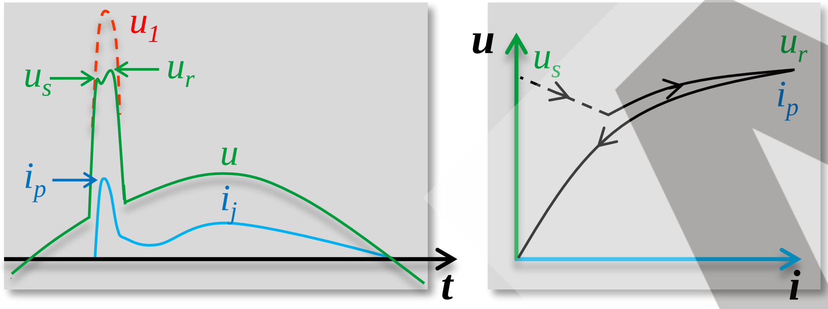
Disk spark gap (2) in series with SiC resistor (1) encased in a porcelain shell

Dividing the spark gap into sections decreases breakdown voltage scatter and flattens the steep transient resulting from flashover.

The nonlinear resistor limits the earth fault current so that arcing is extinguished by itself:

high currents → low resistance

low current → high resistance



u_1 = overvoltage peak (without arrestor)

u = normal operating voltage

u_r = residual voltage

u_s = sparkover (striking) voltage

i_j = follow-through current

i_p = surge current peak

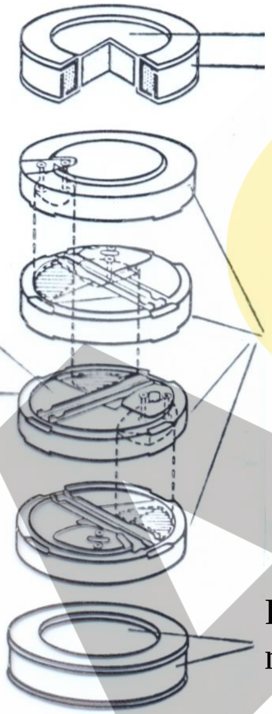
As voltage over the arrestor exceeds **sparkover (striking) voltage u_s**, the spark gap is ignited.

Surge current i_p grows to a value determined by the overvoltage magnitude

Residual voltage u_r (maximum voltage over arrestor during operation) is determined by the discharge current and nonlinear resistor magnitude

After the overvoltage has passed, the arrestor remains conductive and **follow-through current i_j** (fed by the power frequency voltage) is present until the spark gap is extinguished (voltage becomes zero)

Magnetic Blow-out Arrester



Parallel resistance

Coil

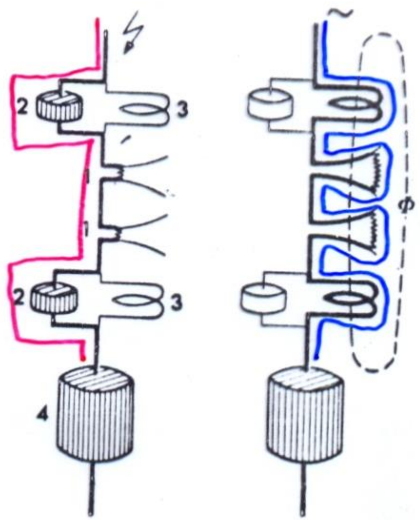
Metal electrode

Ring

Spark gap formed when piling elements (rings) together

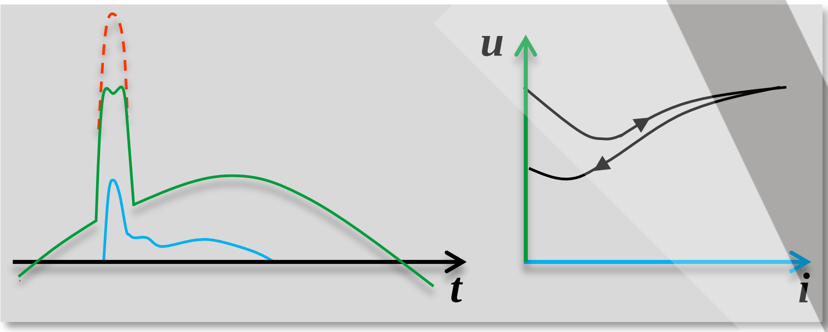
Parallel resistance & coil

Magnetic Blow-out Arrester



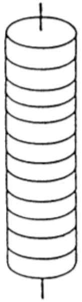
The **high frequency surge current** flows through the parallel resistance [2] of the coils [3] and causes the spark gap [1] to ignite.

- After this, **normal operating frequency current** passes through the coils causing the magnetic field to “**blow**” the arc in the spark gap further.
  - As a result, **arcing voltage increases** and hence, current through the arrestor and voltage over nonlinear resistor [4] (residual voltage) **decreases**.
- When the overvoltage has been discharged through the arrestor, power frequency voltage still feeds **follow-through current**.
  - ✓ Due to the **nonlinearity** of the resistor, current decreases much faster than voltage and arcing over the spark gap is extinguished **before** voltage reaches zero.

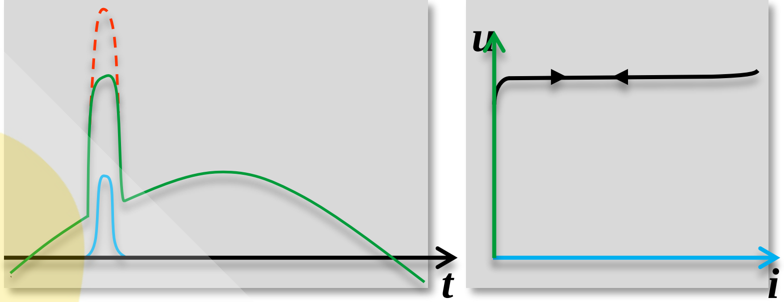


Since extinction does not require zero level voltage, this overvoltage protection works also for DC

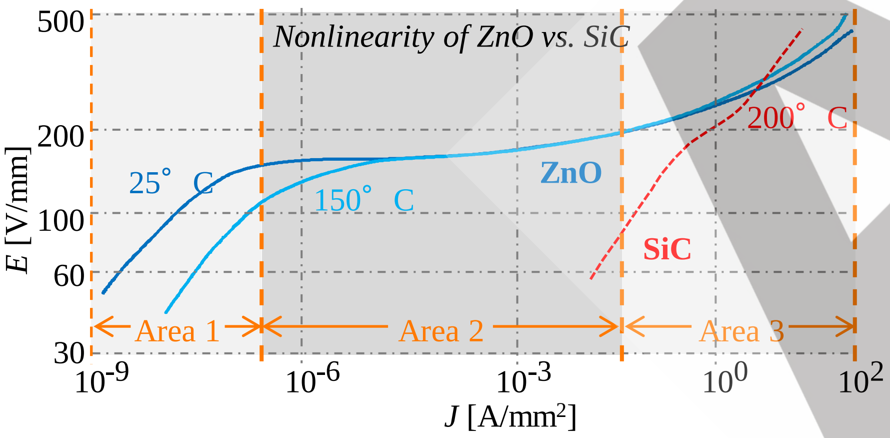
Metal-oxide Varistor



- ZnO + other metal oxides: single core of ZnO covered by a metal oxide surface layer
- Cylindrical mass element connected in series or parallel inside porcelain/polymer shell
- Resistive properties are so **nonlinear** that spark gaps can be left out (*e.g.* $R_{(normal\ operation)} = 1.5\ \mathrm{M\Omega}$, $R_{(discharge)} = 15\ \Omega$)



No rapid voltage changes → No breakdown voltage scatter → Insignificant back current



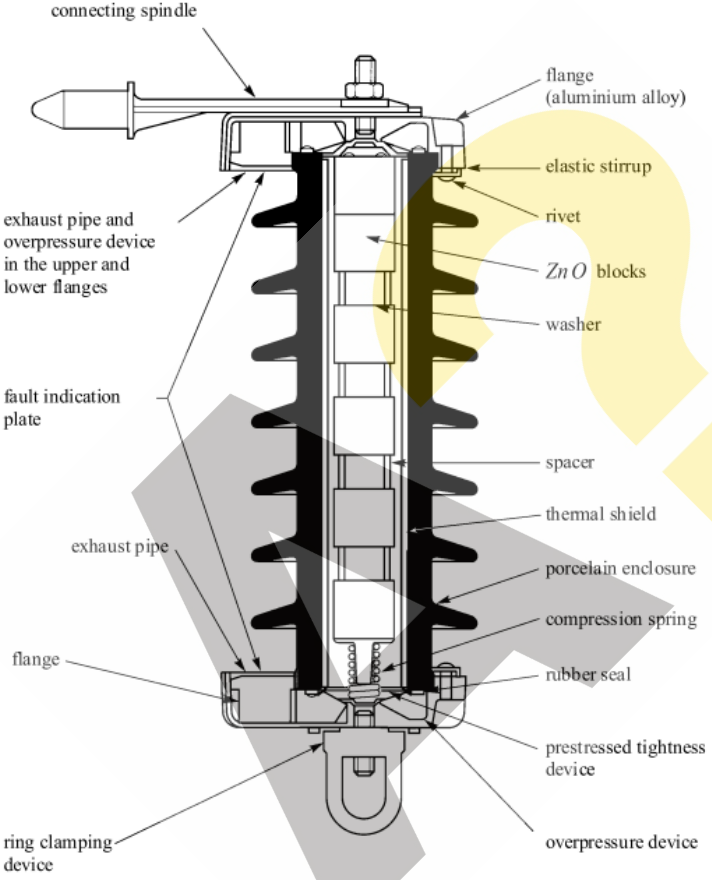
Area 1: ZnO penetrating current decreases radically under voltage threshold value (high resistivity). Poorly conductive surface layer determines magnitude of current.

- At small currents the resistance of the ZnO element decreases as temperature increases (negative thermal coefficient).
- Sufficient cooling needed to assure that the arrestor does not become unstable (thermal run-away) and break.

Area 2: Tunnel effect – more current penetrates through surface layer into ZnO core.

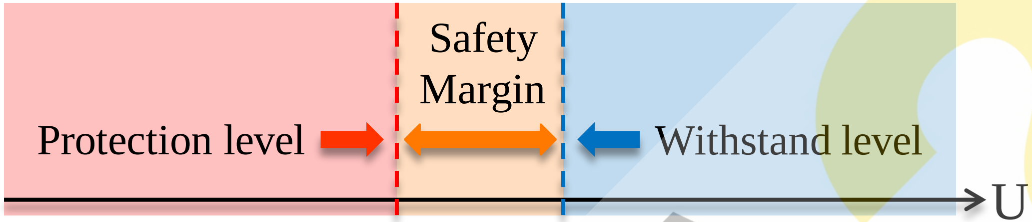
Area 3: Tunnel effect throughout entire material. Magnitude of current determined by core. Resistivity of material is very small.

Metal-oxide Varistor



Arrestor Selection

The arrestor must be selected so that the margin between **protection level** of arrestor and the device's **withstand level** is large enough.



$$U_{cw} = k_c U_{rp}$$

U_{rp} = *representative overvoltage*
U_{cw} = *voltage withstand level of device*
k_c = *protection factor*

The protection level must be set high enough to avoid arrestor operation under **normal continuous operating voltage** but also low enough to avoid overvoltages above the withstand level

Margin exists only if arrestor is *infinitely close* to the protected apparatus

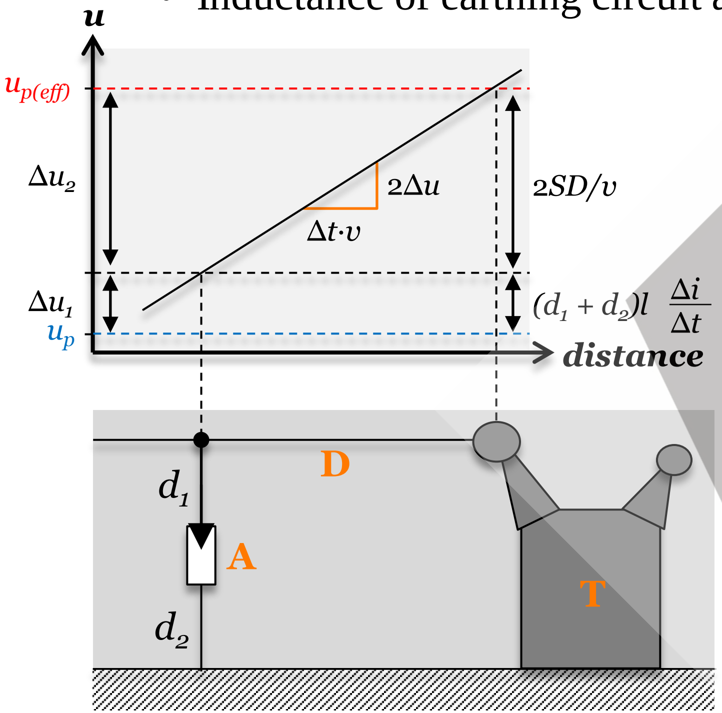
Otherwise, must consider:

- Voltage increase in line caused by propagating overvoltage (superposition of traveling waves)
- Voltage drop caused by surge current at earthing conductor and arrestor connection (coupling)

Arrestor Placement

Protected device (**T**) is at a distance **D** from the arrestor (**A**)

- The front of the voltage pulse is linear
- Inductance of earthing circuit assumed insignificantly small



Effective Protection Level:

$$u_{p(eff)} = u_p + \Delta u_1 + \Delta u_2 = u_p + (d_1 + d_2) l \frac{\Delta i}{\Delta t} + \frac{2SD}{v}$$

u_p = *rated protection level of arrestor*
Δu_1 = *inductive voltage loss at earth and joint coupling*
Δu_2 = *voltage increase between arrestor and protected device*
d_1 = *length of arrestor connection*
d_2 = *length of arrestor earthing*
l = *inductance of joint and earthing conductor (~1 μH/m)*
D = *distance between arrestor and protected device*
S = *steepness of linear impulse voltage*
v = *propagation speed of impulse voltage*

Arrestor Placement

E.g. A **1500 kV/ µs** steep propagating wave is approaching a transformer along a 123 kV line. The voltage **withstand level** of the transformer is **550 kV**. The arrestor is located **10 m** away from the transformer and has a **protection level** of **380 kV**. **Voltage drop** Δu_1 caused by joint and earthing coupling (d_1, d_2) is assumed to be **20 kV**.

$$u_{p(eff)} = u_p + \Delta u_1 + \Delta u_2 = u_p + (d_1 + d_2)\, l\, \frac{\Delta i}{\Delta t} + \frac{2SD}{v}$$

$$= 380\cdot10^3\ \text{V} + 20\cdot10^3\ \text{V} + \frac{2(1500\cdot10^9\ \text{V/s})(10\ \text{m})}{300\cdot10^6\ \text{m/s}} = 500000\text{V} = 500\,\text{kV}$$

Distance and junction results in a 32% increase in protection level

- Safety margin reduced from 170 kV to 50 kV
- Protection factor reduced to $k_c = U_{cw}/U_{rp} = 550/500 = 1.1$

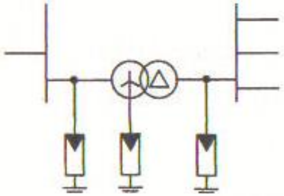
Effective protection level less than withstand level of transformer → OK

If S = 2250 kV/µs, withstand level is exceeded.

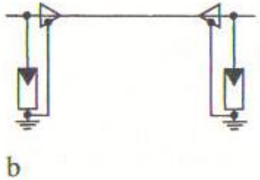
To protect against steep impulses

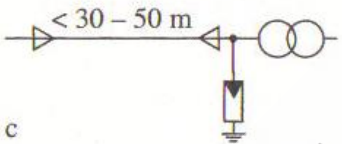
- bring arrestor closer
- select arrestor with lower protection level u_p

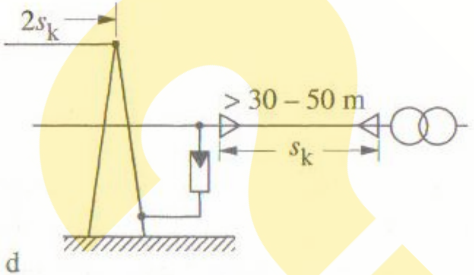
Arrestor Placement

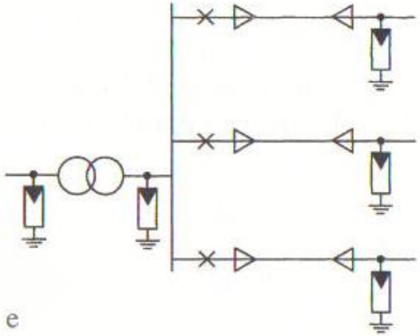


a) Transformer Protection





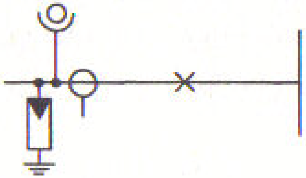




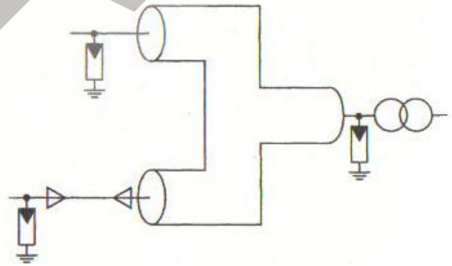
b – e) Cable Protection

Short cables (30 – 50m): Arrestors at end of cable (c)

Longer cables: Risk of back flashover. Arrestors at both ends of cable or use lightning shield wire and minimize earthing resistance. Important to ground arrestor and cable sheath to same point (b)

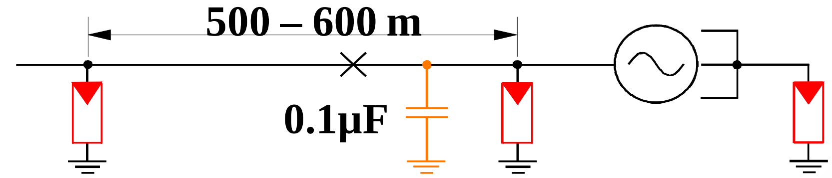


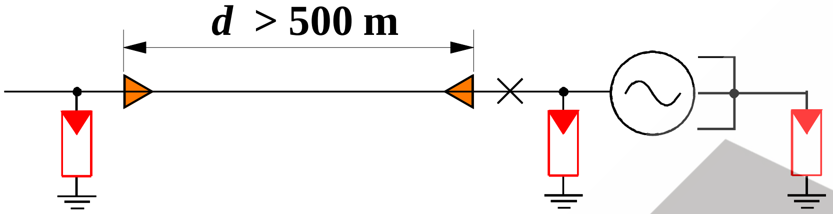
f) Protection of important line-side measuring equipment



g) GIS, RMU protection- arrestors at all line outputs

Generators and motors



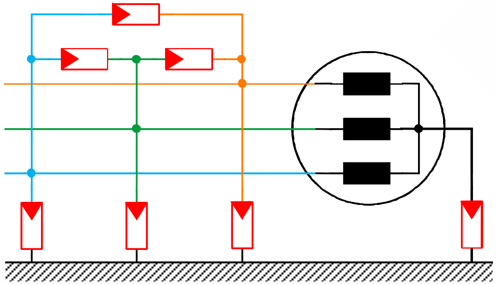


a) Straight connection to overhead line:

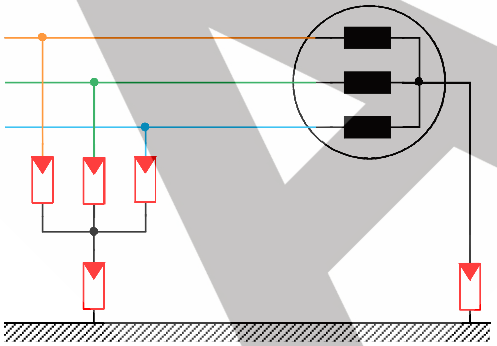
Typically 500m distance between arrestors with protective capacitor (reflections)

b) Connection to overhead line via cable:

Capacitor not needed when distance is over 500 m



a



b

Phase-earth and phase-phase protection:

a) 6 separate arrestors

b) 4 arrestor group

Spark Gap

Spark Gap

Simple device consisting of two electrodes – one connected to the conductor to be protected and the other to ground.

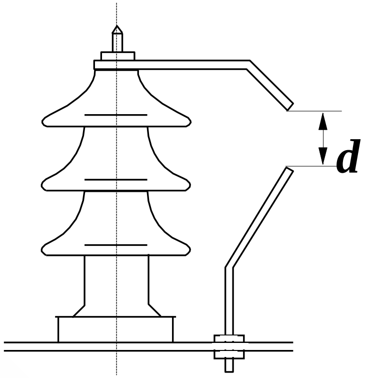
Spark gaps form a weak point enabling overvoltages to flow to earth instead of to the protected device.

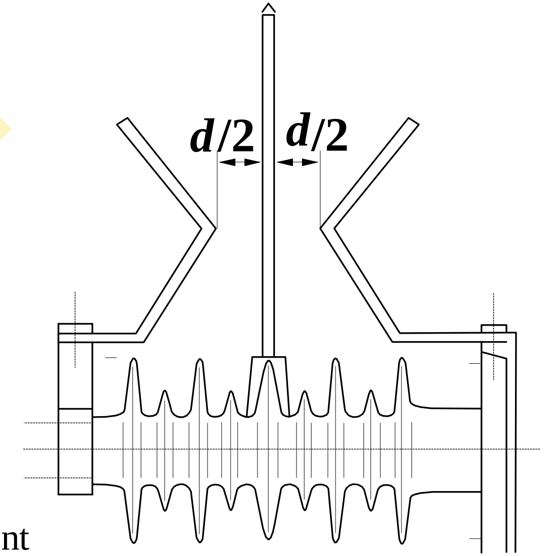
Breakdown voltage can be adjusted

Surge arresters are more expensive and require monitoring (arrester can fail)

⇨ **Cheaper** and **simpler** solution for protecting smaller pole transformers is to use a spark gap

- at most 240 kVA, 24 kV transformer (FIN)
- transformer must withstand spark gap overvoltage and steep voltage transient

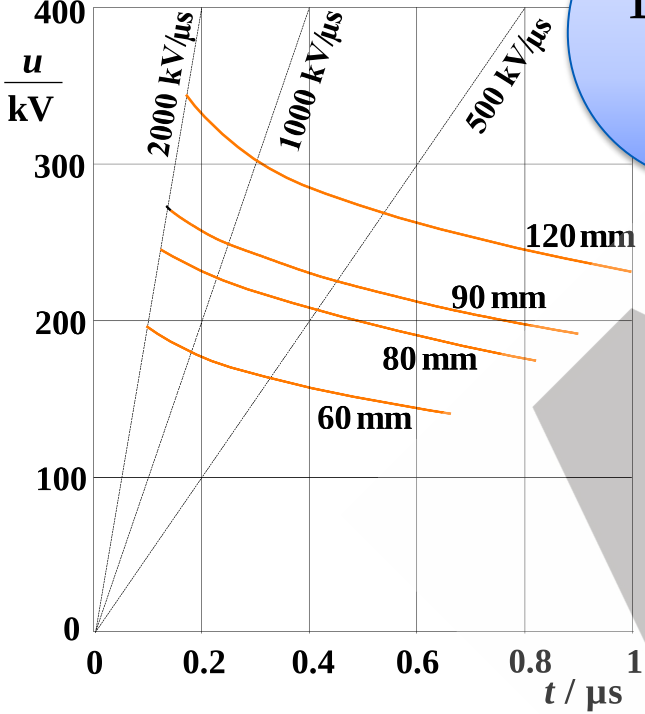




Spark Gap

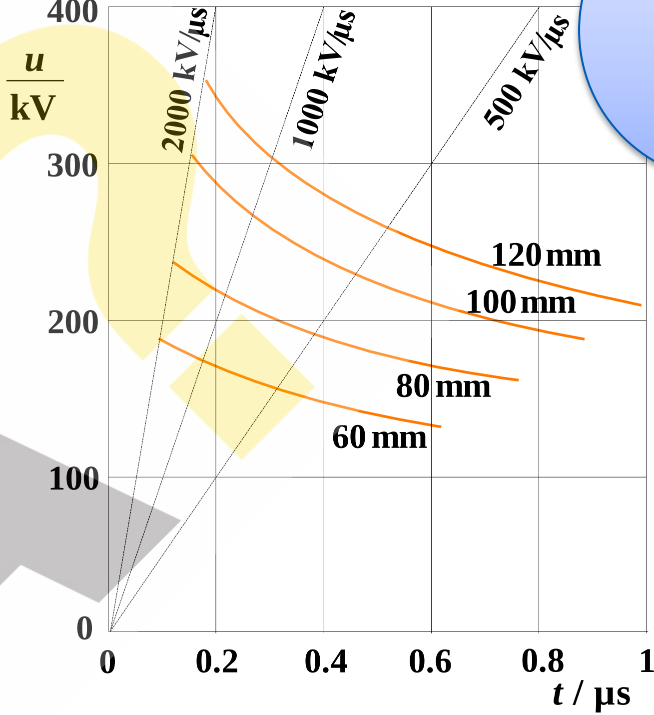
Voltage-Time Curve:

Double gap



Voltage-Time Curve:

Single gap



500 kV/µs: Direct lightning stroke to conductor

1000 – 2000 kV/µs: Back flashover (rare)

Spark Gap

Inter-electrode distance *d* of spark gap:

- **Large enough** to avoid breakdown by temporary overvoltages and small transients
- **Small enough** to protect against fast-front transient voltages (lightning)

Problems with spark gaps:

⇨ Gap operation causes an **earth fault**

Short zero voltage period needed to remove fault (requires fast reclosing system)

○ Polarity dependence ○ **Weather conditions**

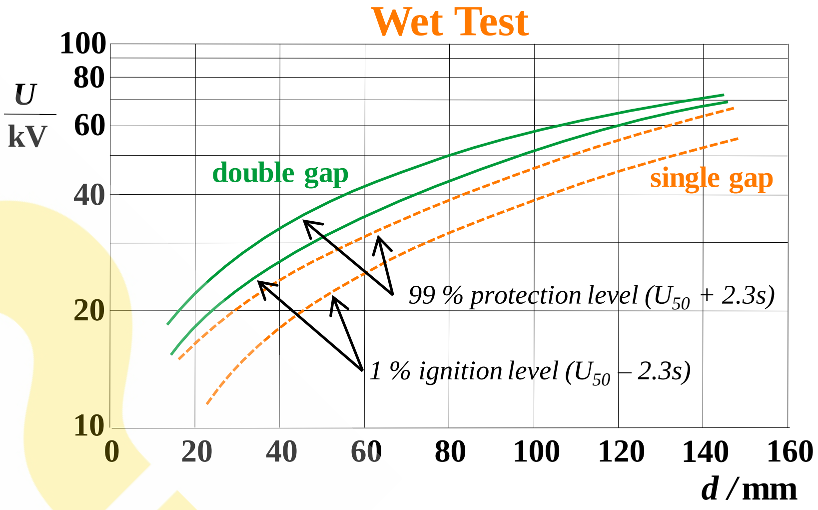
Temperature, humidity, and pressure affect ionization

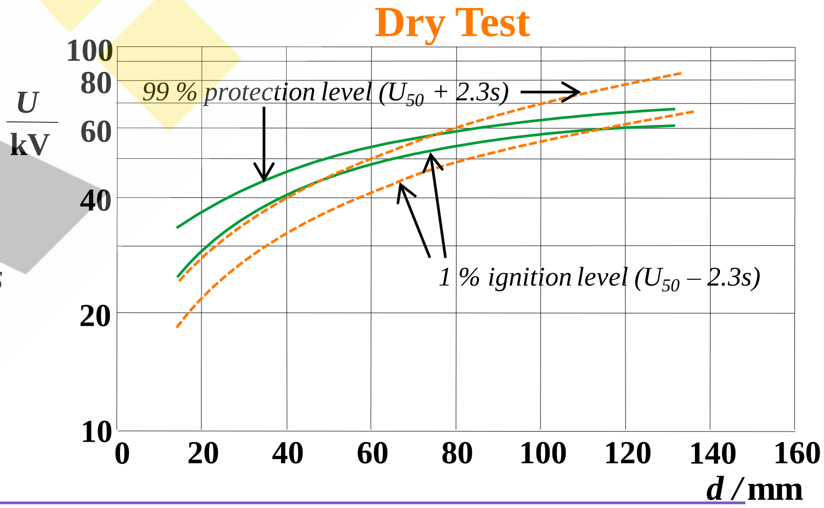
⇨ Large operating **voltage spread**

Up to 40%, also dependent on overvoltage shape, i.e. steepness

Spark gap implementation:

- Reasonable number of atmospheric overvoltages
- Short outages allowed





Very-Fast-Front Overvoltages

a.k.a. ***Very Fast Transients***

High Voltage Testing

Voltage Testing

- Voltage withstand strength

Current Testing

- Thermal and dynamic current (arcing) withstand

Equipment Testing

- Mechanical and other tests (not in this course)

⇨ Testing done at:

Laboratory

Manufacturing Line (Factory)

On-Site

Official tests according to international standards (IEC, CENELEC)

- Detail instructions and goals for tests (including testing environment)

High Voltage Testing

Purpose:

To confirm all parties that the electrical insulation and installation fulfills all necessary requirements and standards

To find insulation errors which may affect the short-term or long-term performance of the device

To avoid loss of:

- Life
- Environment
- Assets

High Voltage Testing

Testing costs are a significant portion of purchasing costs

- Most testing is involved in **production** and **acquisition**
- Standards and tests specified in purchasing offer and contract

Designing

Design Testing

Prototype

Type Testing

Assurance of correct design

Extensive ensemble of testing to ensure suitability of equipment type. Testing repeated every 3 – 5 years to give customer the updated results.

Mass Production

Routine Testing

Assurance of correct fabrication

Small scale testing for every produced device. Find defective specimen.

Finished Product

Sample Testing

Extended routine testing

Random testing of small portion of manufacture batch.

Acceptance test – agreed upon in purchasing contract

Not a standard test. Typically repeating parts of type or sample tests

Usually done at manufacturer’s laboratory

*Also **on-site** – e.g. cable installation may stress cable. Tests are repeated after installation.*

Testing requirements

Representativity

Testing must represent the **practical stresses** for which the testing is conducted.

Repeatability and Reproducibility

Test results must be the same regardless of testing time and location (**repeatability**) and new tests must be the same for similar test objects (**reproducibility**)

Independence

Results should not be dependent on **prior stress**. Dependence is not rare:

- Effect of voltage stress has not been removed before following test (time interval too short)
- Mechanical stress affects the voltage stress results (both mechanical and voltage test must be viewed as single test and repeated in the same manner)

Selectivity

Results of testing must enable a **conclusion** (acceptance/rejection of test object). Clear boundary.

Standards

- The goal is to promote the fulfillment of requirements for testing.

Benefits from the best practices
Easier definition of requirements for investments


GENERAL STANDARDS
EQUIPMENT STANDARDS

Reduced integration costs
Promote competition

International IEC, European EN, American ANSI and IEEE standards

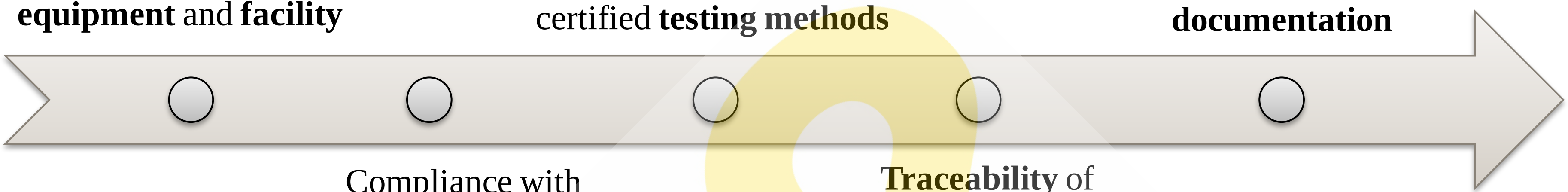
⇨ Long history of cooperation and goal for uniformity

e.g. CENELEC confirms IEC standards into European EN and Finnish SFS-EN standards

IEC 60071	*Insulation coordination (overvoltage protection)*
IEC 60060	*Testing and measurements*
IEC 61180	*HV testing technique for LV equipment*
IEC 60694	*HV switchgear*
IEC 61083	*Digital recording instrumentation*
IEC 60270	*PD measurements*
IEC 61211	*Breakdown tests for insulators*
IEC 60410	*Sample acquisition and statistical processing*

Finland: SFS www.sfsedu.fi

Quality of Testing



Suitability and condition of **equipment** and **facility**

Compliance with **standards**

Qualified **personnel** and certified **testing methods**

Traceability of measurements

Sufficient **documentation**

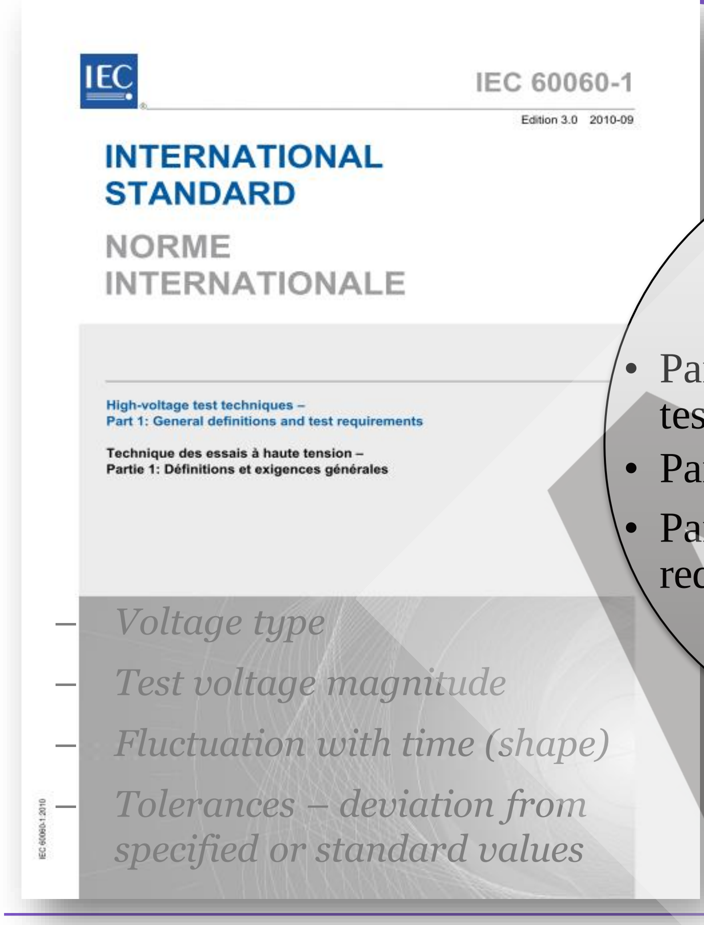
Accreditation

Indication of **competence** and **validation** of laboratory quality

- Independent **outside evaluation** of test procedures (MIKES - *Centre for Metrology and Accreditation*)

Test Voltages

Standard Test Voltages



IEC 60060-1

Edition 3.0 2010-09

INTERNATIONAL STANDARD

NORME INTERNATIONALE

High-voltage test techniques –
Part 1: General definitions and test requirements

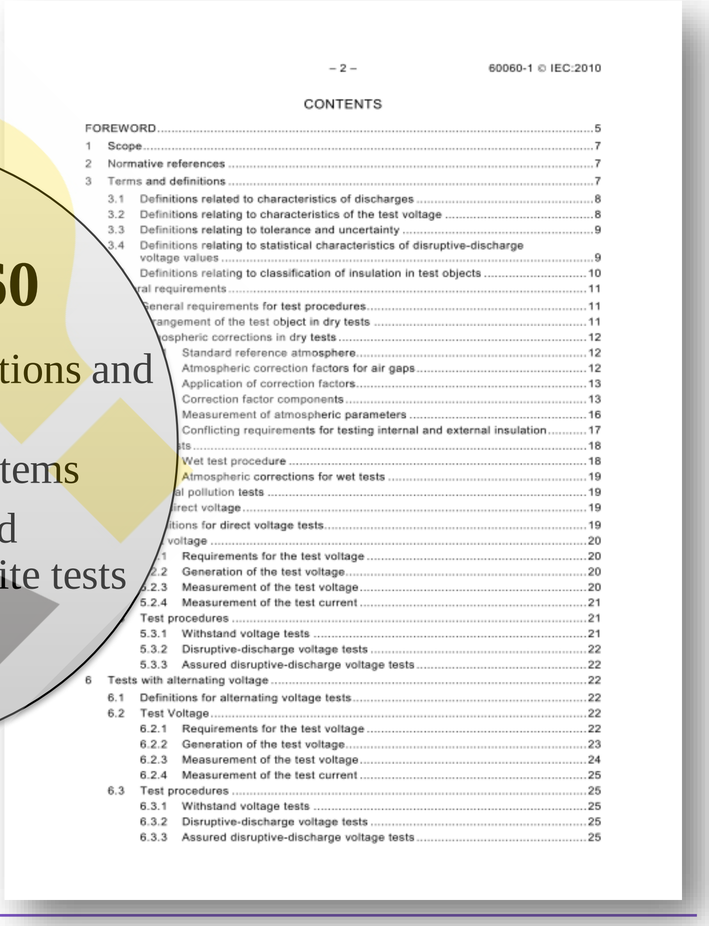
Technique des essais à haute tension –
Partie 1: Définitions et exigences générales

IEC 60060-1:2010

- *Voltage type*
- *Test voltage magnitude*
- *Fluctuation with time (shape)*
- *Tolerances – deviation from specified or standard values*

IEC 60060

- Part 1: General definitions and test requirements
- Part 2: Measuring systems
- Part 3: Definitions and requirements for on-site tests



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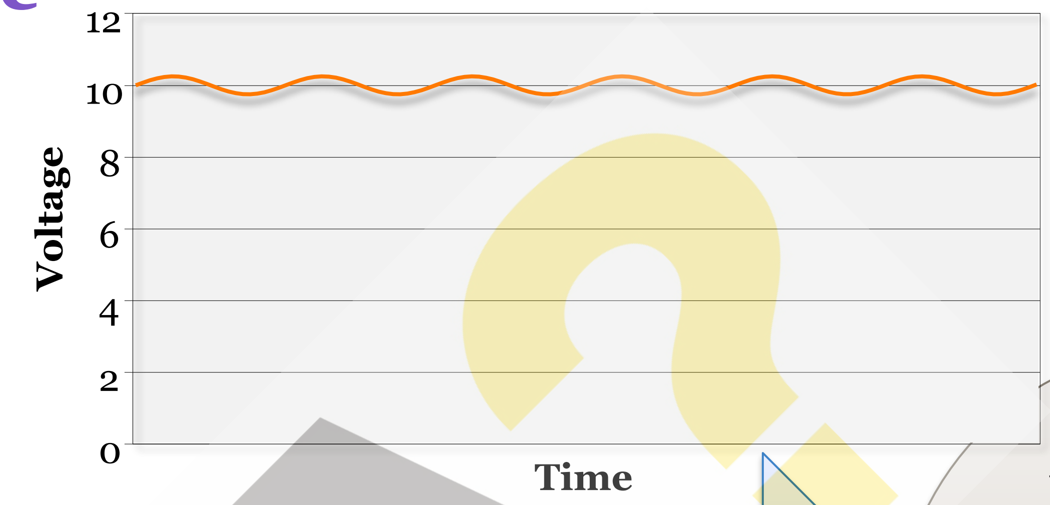
DC Voltage



Terminology

- **Value of the test voltage**: $U_{avg} = 10$
- **Ripple** = *periodic deviation from the arithmetic mean value of the test voltage*
- **Ripple amplitude**: $(U_{max} - U_{min})/2 = 0.25$
- **Ripple factor** *(ratio of the ripple amplitude to the value of the test voltage)*: 0.25/10 = 0.025 (2.5%)

Requirements

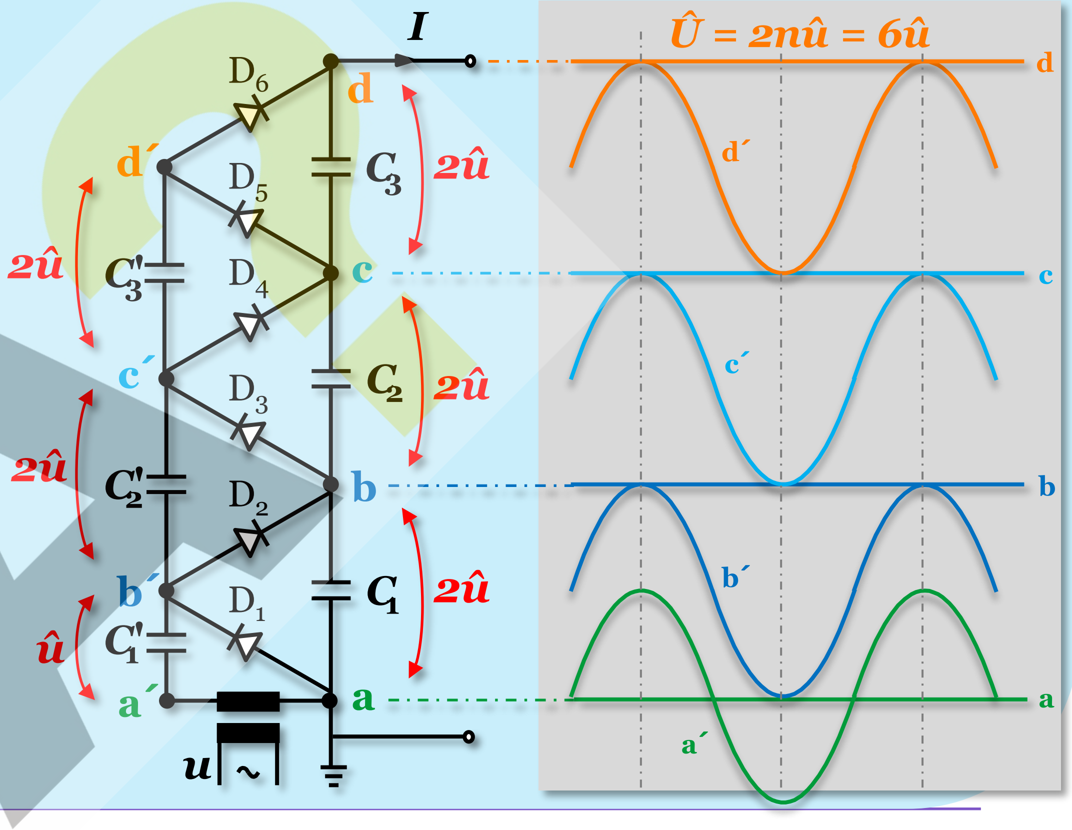
- Ripple factor ≤ 3%
- t < 60 s: value of test voltage maintained within ±1 % of specified value
- t > 60 s: value of test voltage maintained within ±3 % of specified value

DC Sources

CASCADE CIRCUIT– converts low level AC to higher level DC using a ladder construction of diodes and capacitors

Cockroft-Walton (1932): ***CW multiplier***

Heinrich Greinacher (1919): ***Greinacher multiplier***



The supply voltage charges C_1´to û. During the positive half-cycle D_2 is conducting and charges C_1. As the AC signal reverses polarity D_1 starts to conduct now further charging C_1 to 2û.

With each change in input polarity, the capacitors add to the upstream charge.

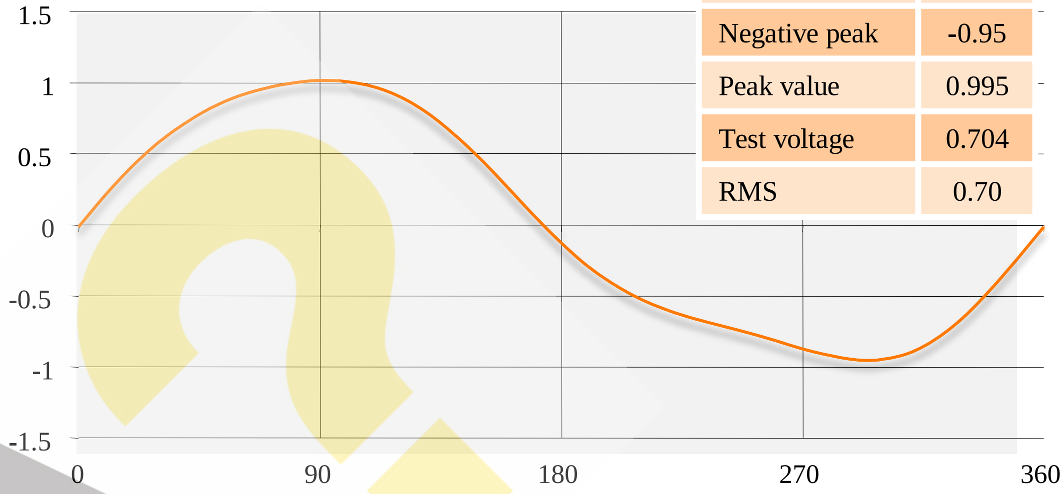
The increase in voltage, **assuming ideal components**, is two times the input voltage times the number of stages

$$\hat{U} = 2n\hat{u}$$

AC Voltage

Terminology

- **Peak value** = average of the magnitude of the positive and negative peak values
- **Value of the test voltage** = peak value divided by √2
- **RMS value** = square root of the mean value of the square of the voltage values during a complete cycle



Quantity	Value
Positive peak	1.04
Negative peak	-0.95
Peak value	0.995
Test voltage	0.704
RMS	0.70

Breakdown depends on the maximum level of voltage stress

⇨ **Peak value** of alternating voltage, not the RMS-value

Requirements

Frequency 45…65 Hz

Difference in the magnitudes of the positive and peak values less than 2 %

Ratio of peak to r.m.s. values equals to √2 within ± 5% (U_{peak}/U_{rms} = 1.34 … 1.48)

t < 60 s: values of test voltage maintained within ± 1 % of the specified value

t > 60 s: values of test voltage maintained within ± 3% of the specified value

Value of the test voltage
≠
RMS unless *sinusoidal*

AC Sources

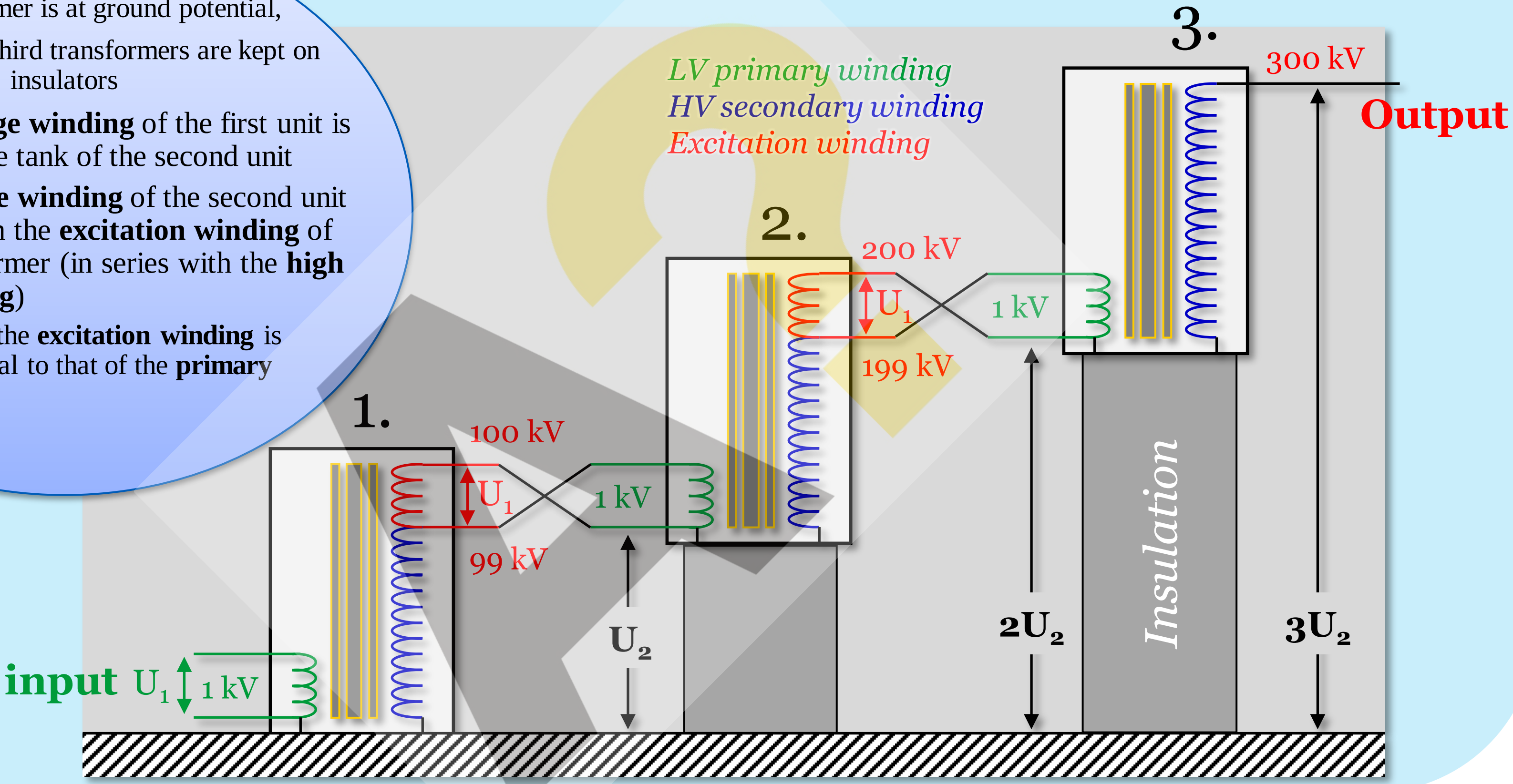
CASCADE TRANSFORMER

- Connecting HV windings in series

First transformer is at ground potential,

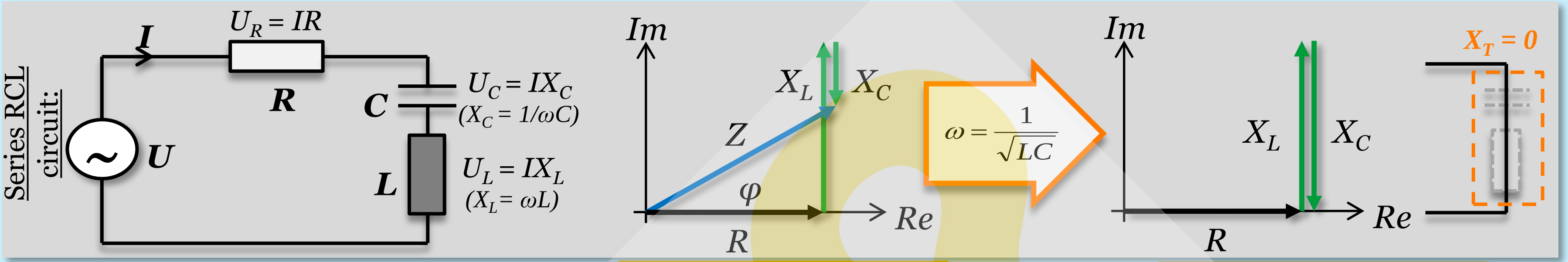
The second and third transformers are kept on insulators

- The **high voltage winding** of the first unit is connected to the tank of the second unit
- The **low voltage winding** of the second unit is supplied from the **excitation winding** of the first transformer (in series with the **high voltage winding**)
  - The rating of the **excitation winding** is almost identical to that of the **primary winding**.



AC Sources

RESONANT TRANSFORMERS – Resonance to multiply input



$$X_L \neq X_C$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

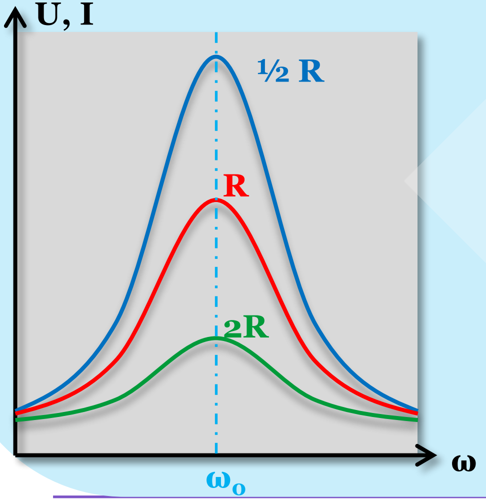
$$\varphi = \tan^{-1}\left(\frac{X_L - X_C}{R}\right)$$

$$X_L = X_C$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = R$$

$$\varphi = 0$$

$$\boxed{U_{out} = Q \cdot U_{in}}$$



$$\textbf{Quality Factor Q} = \frac{\text{Output Reactive Power}}{\text{Input Real Power}} = \frac{\text{Test Specimen Reactive Power}}{\text{Reactor Losses + Test Load Losses}}$$

Test Specimen Reactive Power = $(U_{out})^2 / X_c$ *where* $X_c = 1 / 2\pi f C_{load}$

Reactor Losses = Real power dissipated in reactor. Resistive losses in reactor windings, magnetic losses in reactor core and stray losses in tank structure

Test Load Losses = Real power dissipated in test object. Losses in insulation due to leakage current, losses in termination equipment, and external stray losses

Switching impulse (SI, 250/2500)

The standard switching-impulse voltage is an impulse having time to peak T_p of 250 µs and a time to half-value T_2 of 2500 µs. It is described as a 250/2500 impulse.

Switching impulse

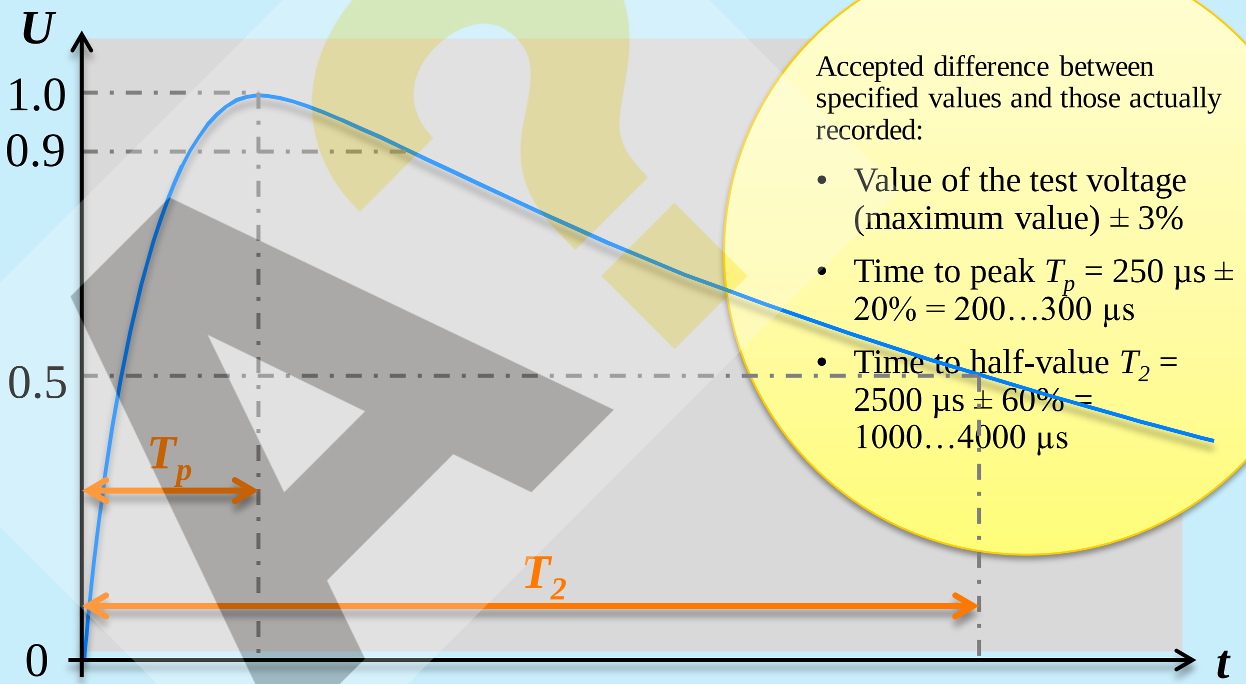
Impulse voltage with a front time of 20 µs or longer

Time to peak T_p

Time interval from the true origin to the time of maximum value of a switching-impulse voltage

Time to half-value T_2

Time interval between the true origin and the instant when the voltage has first decreased to half-the maximum value.

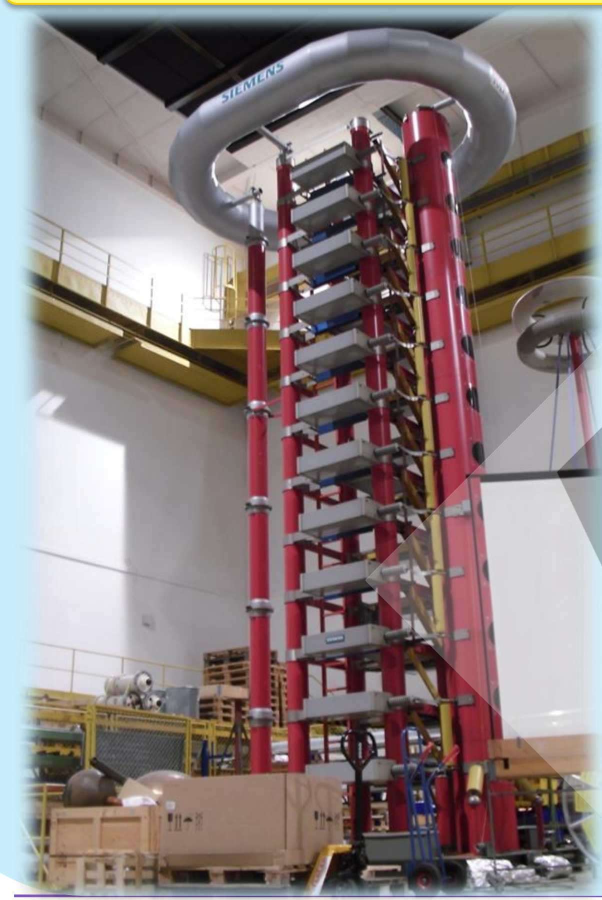


Accepted difference between specified values and those actually recorded:

- Value of the test voltage (maximum value) ± 3%
- Time to peak T_p = 250 µs ± 20% = 200…300 µs
- Time to half-value T_2 = 2500 µs ± 60% = 1000…4000 µs

Indoors ~ 400 – 4000 kV

Outdoors ~10 MV


2.4 MV – TU Dresden


3.6 MV – General Electric Company

Testing and Diagnostics

- Diagnostic Tools
  - Processing Results
    - Typical Tests

Testing vs. Diagnostics

- *Partial discharge measurement*
- *Dielectric response measurement*
- *Magnetic flux measurements*
- *Harmonics analysis*
- *Thermal imaging*
- *Gas analysis*
- ***Sensations** (visual, hearing, smell)*

Diagnostic Tools

Testing can be **destructive**

Diagnostics cannot

Processing Test Results

Breakdown voltage is a **stochastic (random) variable** with many dependant factors:

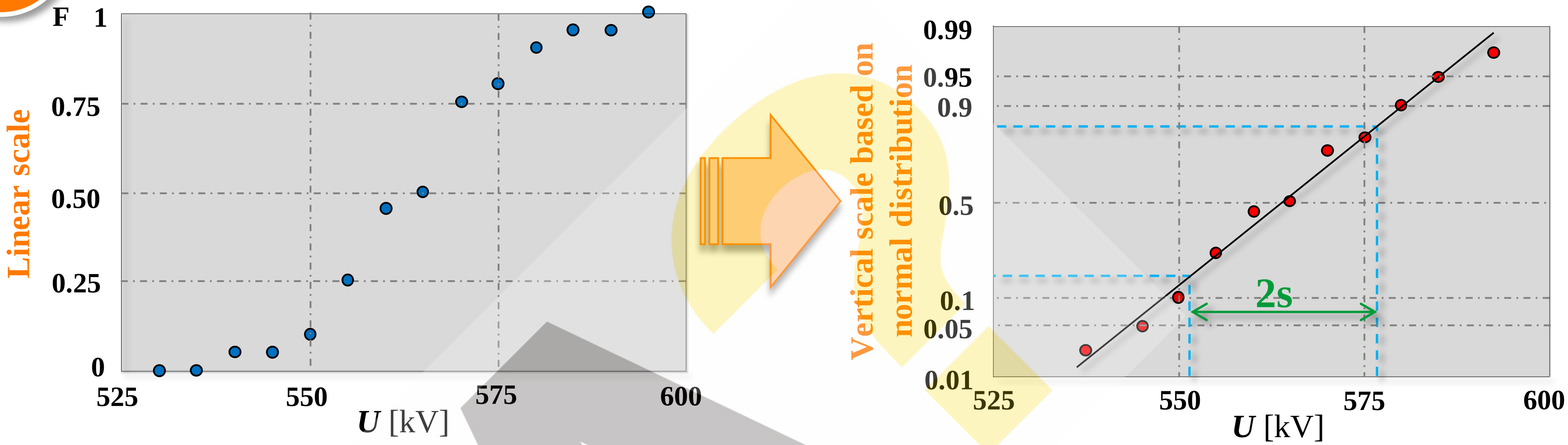
- Discharge mechanisms
- Non-ideality of insulation
- Differences between same type of insulation
- Impurities (pre and post manufacturing)
- Weather, environment, external influence
- Variations in test procedures

⇨ **Statistical mathematics** and **probability calculations** needed in analyzing results.

Test results should be presented in a clear and brief manner using simple parameters – e.g. 50% breakdown voltage and standard deviation

Fluctuation can be so significant that a single withstand voltage result expressed without probability data is meaningless

E.g. Nonlinear S-shape distribution can be made linear by changing coordinate system



Using linear regression (least square method), points can be fitted to a line of best fit with which distribution parameters can be analyzed

- *50% breakdown voltage U_{50} correlates to probability 0.5*
- *Standard deviation $s = U_{50} - U_{16}$*
- *68% of all measured points will fall within the range $U_{50} \pm s$*
- *95% of all measured points will fall within the range $U_{50} \pm 2s$*

IEC 60060-1 (2010):

U_p = p% disruptive-discharge voltage of a test object

prospective voltage value which has p% probability of producing a disruptive discharge on the test object.

U_{10} = "statistical withstand voltage"
U_{90} = "statistical assured disruptive discharge voltage"

U_{50} = 50% disruptive discharge voltage of a test object

prospective voltage value which has a 50% probability of producing a disruptive discharge on the test object.

U_a = Arithmetic mean value of the disruptive-discharge voltage of a test object

$$U_a = \frac{1}{n}\sum_{i=1}^{n} U_i$$

where U_i = measured disruptive-discharge voltage
n =number of observations (discharges)

Note: For symmetric distributions U_a is identical to U_{50}

Tests produce a probability distribution expressing breakdown (or flashover) probability as a function of voltage. The distribution is experimental and only valid for the performed test.

Each test will produce a **slightly different distribution**. Even when:

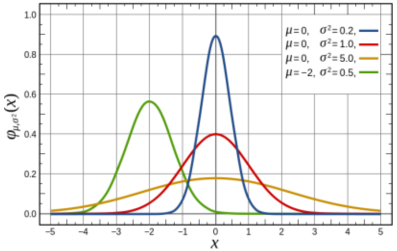
- test is repeated immediately
- same test specimen in re-installed
- similar test specimens are utilized
- different laboratories, different times, different equipment, different people

Results become more accurate if tests are repeated very many times

- time consuming → environmental conditions do not remain constant
  → test sample does not remain constant

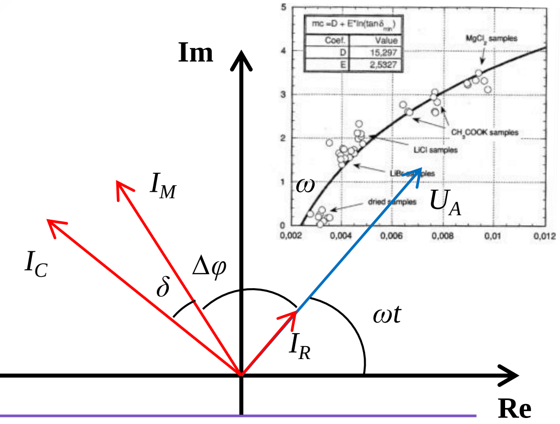
An experimentally obtained distribution from a narrow range of results is poorly applicable for systematic analysis

- For this reason it is reasonable to generalize results by comparing them to **known mathematical models** – probability distributions (commonly Gaussian and Weibull).



Typical Tests

AC-voltage test and impulse voltage test	Short circuit test, arc fault test	Temperature rise test	Partial discharge test	Dissipation factor measurement
• Verify ***integrity of insulation*** between live parts and earth and between different voltage levels (turn-to-turn, layer-to-layer)	• Verify ***mechanical rigidity*** against high dynamical forces caused by short circuit currents. • Safe operation against high pressure and temperature effects of arc	• To verify that apparatus does not ***overheat*** during the operation	• To detect harmful local ***discharges*** which do not completely bridge the insulation between conductors before they lead to complete failure.	• Quality measurement to measure ***losses*** of the insulation (moisture content)



AC & DC Testing

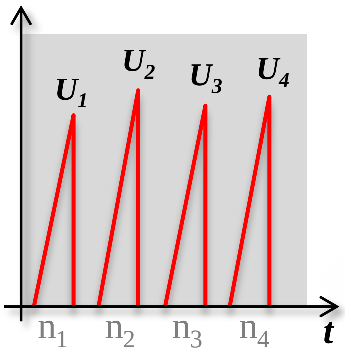
Number of measurements in a test series should be at least 10

($n \geq 10$)

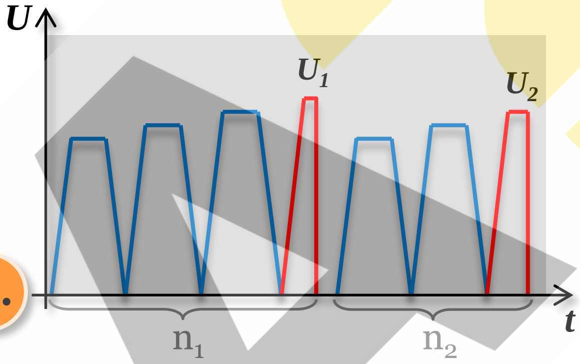
Typical testing methods:

1. Increasing voltage at a specified rate (kV/s) until breakdown occurs **(a)**
2. Maintain a given voltage for a specified duration (60 s, 5 min, 24 h)
    - Increase voltage as separate time intervals (return to zero before next voltage level) **(b)**
    - Increase voltage at subsequent time intervals **(c)**

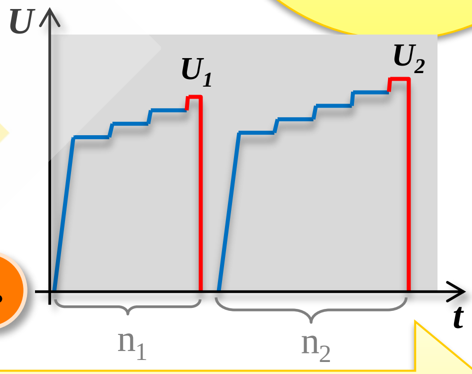
a.



b.



c.



Average $U_{50} = \frac{\sum U_i}{n}$ **Standard deviation** $s = \sqrt{\frac{\sum (U_{50} - U_i)^2}{n-1}}$

Lightning Impulse (LI) Testing

Typical test methods:

1. Increasing voltage until breakdown
2. Withstand test **15/2** or **3/0** – 2 breakdowns in 15 pulses (*self-restoring insulation*). 3/0 test for non *self-restoring insulation*.
3. **Up and down** test – voltage is increased in steps until breakdown occurs. Voltage is increased or decreased depending on the occurrence of breakdown

U [kV]																																								(0)	(x)	(0+x)
520	O																																									
530		O																																								
540			O												O																O									3	0	3
550				O				O						X		O						O								X		O		O						6	2	8
560					O		X		O				X				O				X		O						X				X		O				O	6	5	11
570						X				O		X						O		X				O				X								O		X		4	5	9
580											X								X						O		X										X			1	4	5
590																										X														0	1	1
																																								20	17	N = 37

M. Pourakbari Kasmaei, 2020

Lightning Impulse (LI) Testing

U [kV]		(0)	(x)	(0+x)
520	O			
530	O			
540	O O O	3	0	3
550	O O X O O X O O	6	2	8
560	O X O X O X O X X O O	6	5	11
570	X O X O X O X O X	4	5	9
580	X X O X X	1	4	5
590	X	0	1	1
		20	17	N = 37

Nj is the number of pulses (o+x) at voltage U and N is the total number of pulses (e.g., 37)

$$U_{50} = \frac{\sum N_j U_j}{N}$$

$$s = 1.62 \cdot \Delta U \left(\frac{s_u^2}{\Delta U^2} + 0.029 \right)$$

ΔU = voltage interval

Continue until 30 – 40 results acquired

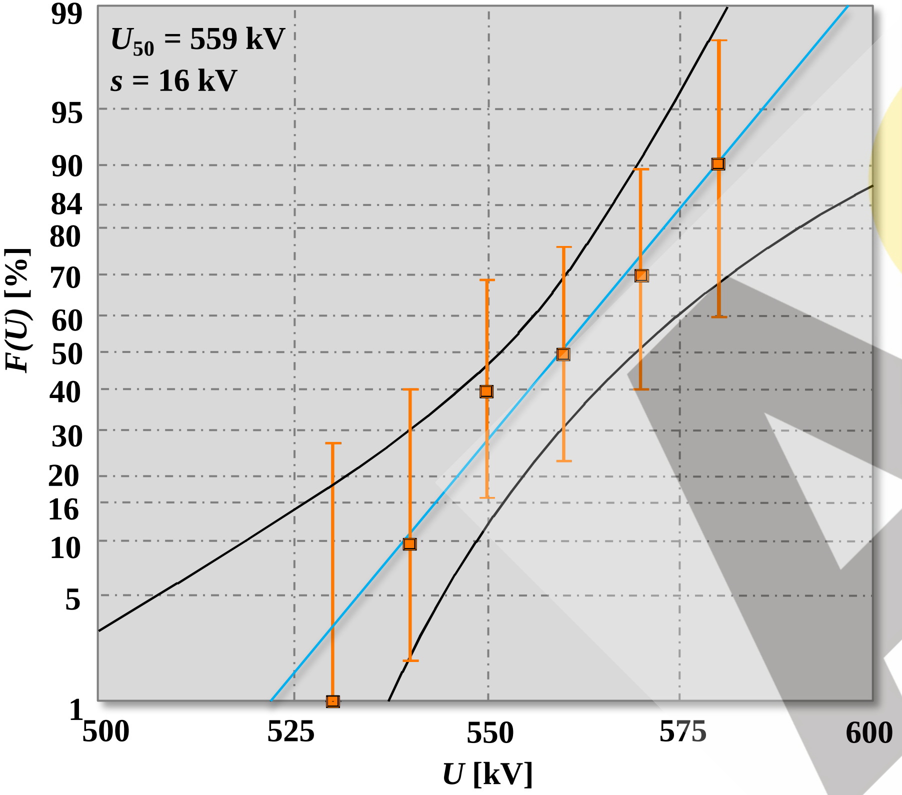
- Only data from levels with more than 1 pulse used

$$s_u^2 \begin{cases} s = \sqrt{\dfrac{\sum (U_{50} - U_i)^2}{n-1}} \\ U_{50} = \dfrac{\sum U_i}{n} \end{cases}$$

Use either (0) or (x) column depending on which is fewer

Lightning Impulse (LI) Testing

4. Multi-level method



U [kV]											(O)	(X)	(O+X)	n_j/N_j
530	O	O	O	O	O	O	O	O	O	O	10	0	10	0.00
540	O	O	O	O	O	X	O	O	O	O	9	1	10	0.10
550	O	X	O	X	O	X	O	O	X	O	6	4	10	0.40
560	O	X	O	O	X	O	X	X	O	X	5	5	10	0.50
570	X	O	X	O	X	X	O	X	X	X	3	7	10	0.70
580	X	X	X	X	X	X	X	X	O	X	1	9	10	0.90

50 % breakdown probability U_{50} = 559 kV

Standard deviation is the difference between 50% and 16% coordinates:

s = 16 kV (2.9% of U_{50})

High Voltage Measurement Systems

- Test Setup
  - Voltage Divider
    - Measurement Cable
      - Digitizer
        - Current Measurements

High Voltage Measurement System

Typical HV measurement setup includes:

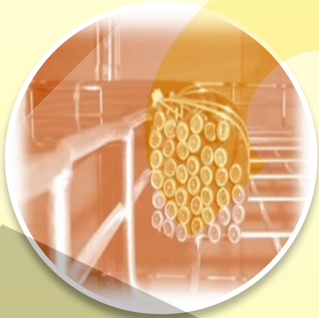
Voltage source

(Transformer)

Converter

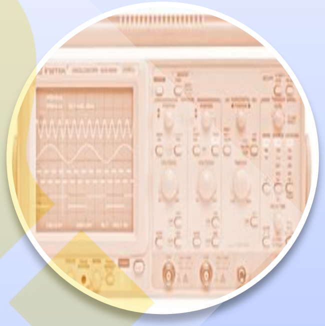
Voltage divider

Instrument transformer



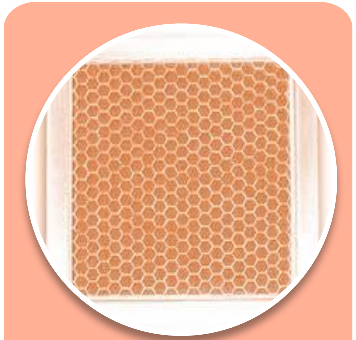
Transmission system

- From converter to measuring instrument
- Including attenuators, matching impedance, terminators



Indicating or recording instrument

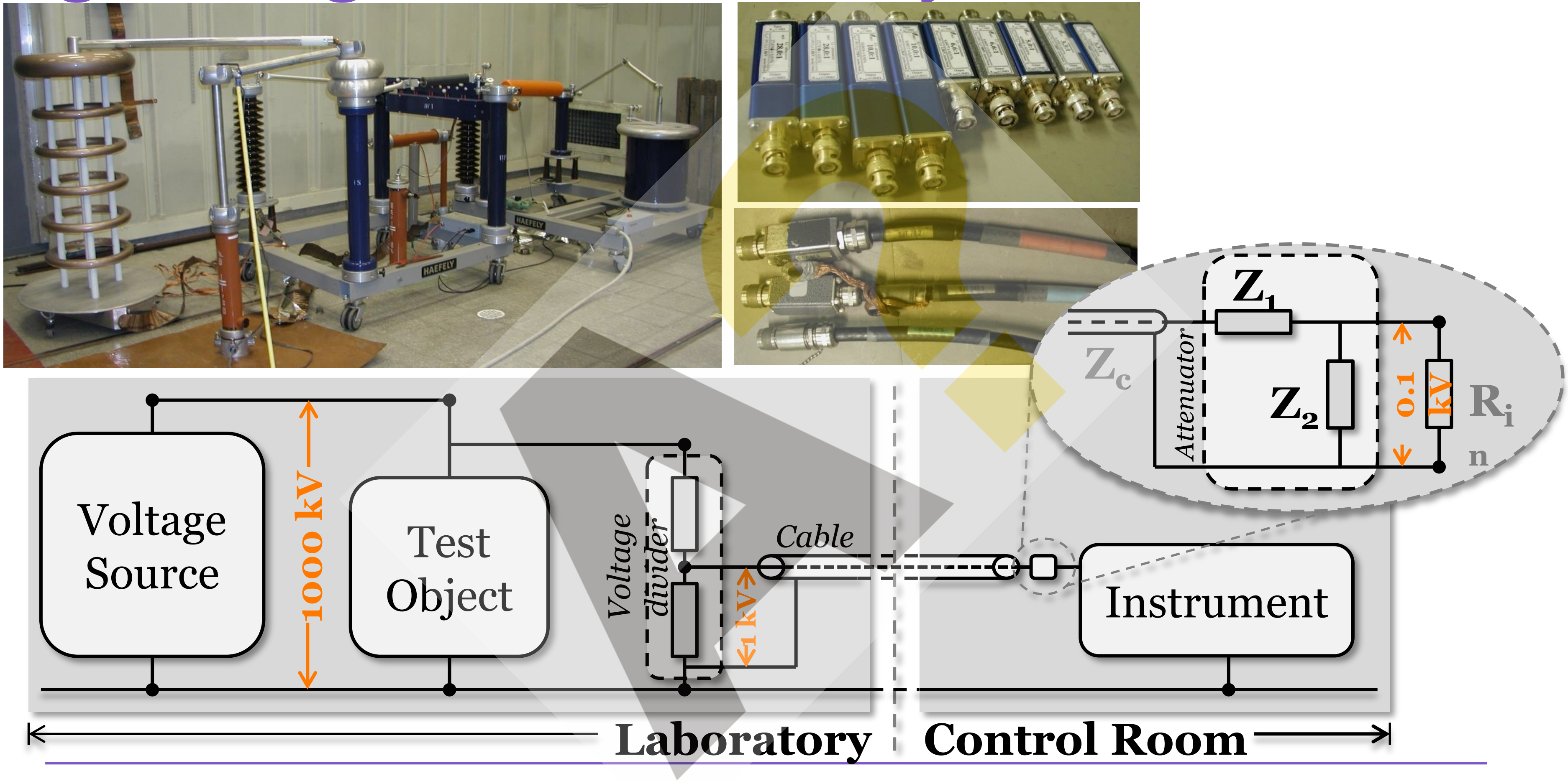
- Voltmeter, ammeter, oscilloscope, digital recorder
- Instrument typically includes internal attenuators which can be used as matching impedance



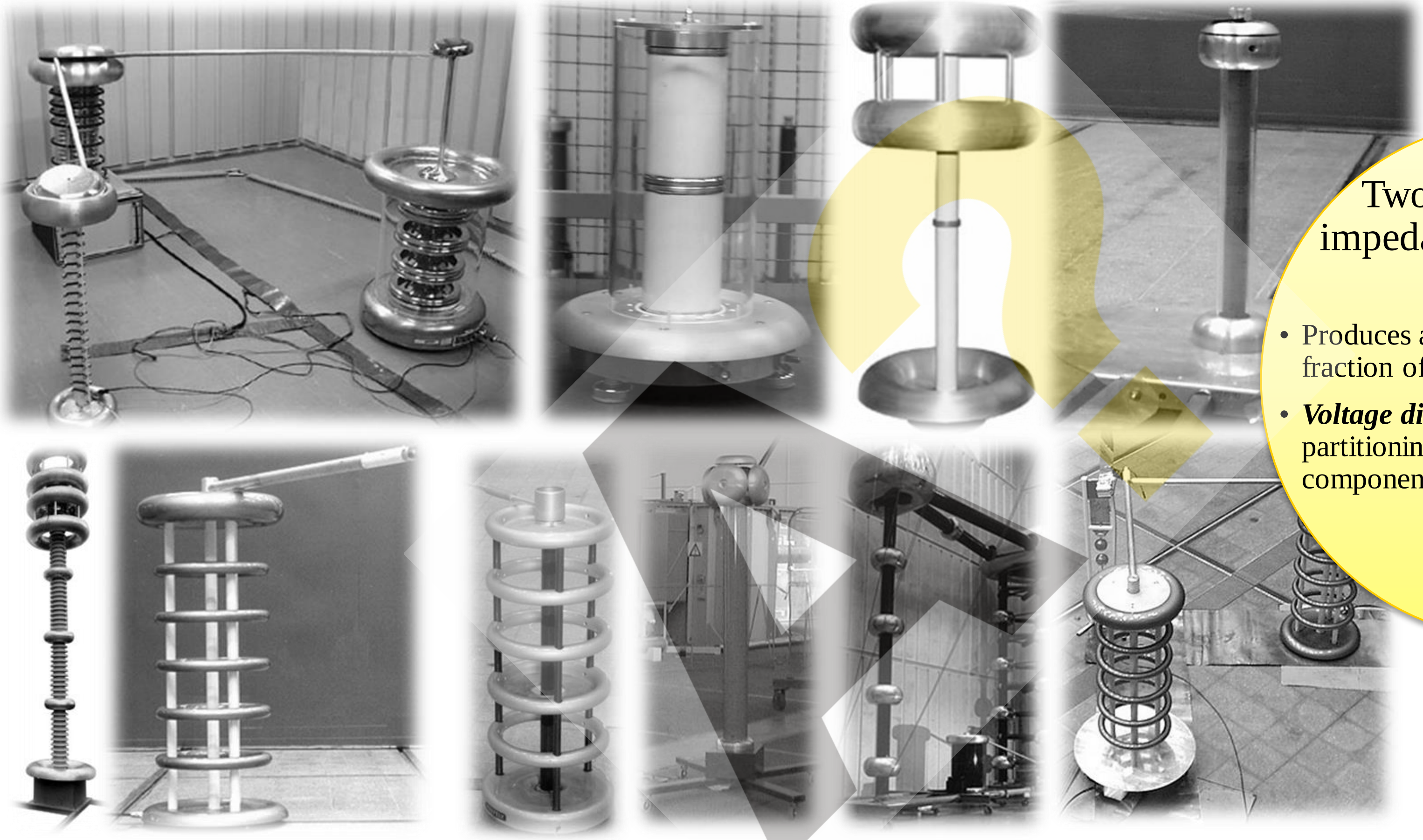
Interference shielding

Earthing system

High Voltage Measurement System



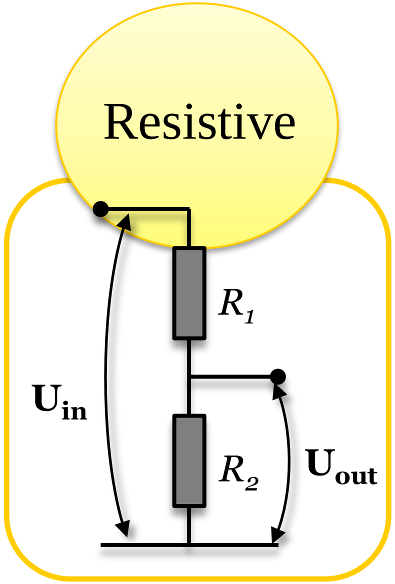
Voltage divider

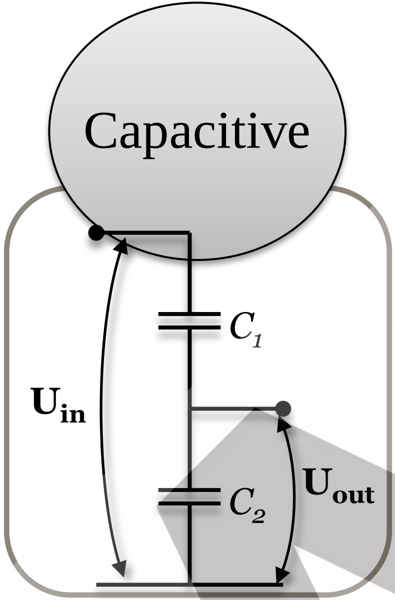


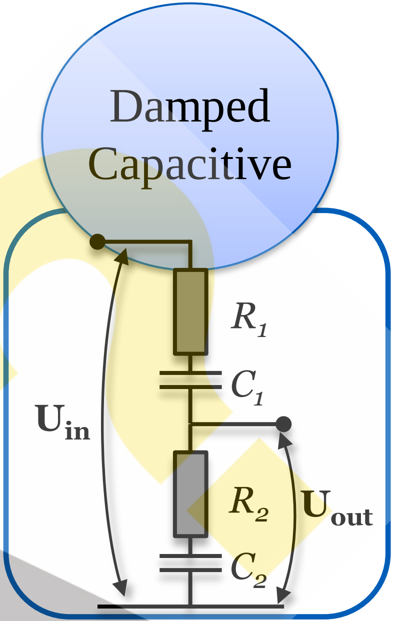
Two highly unequal impedances connected in series

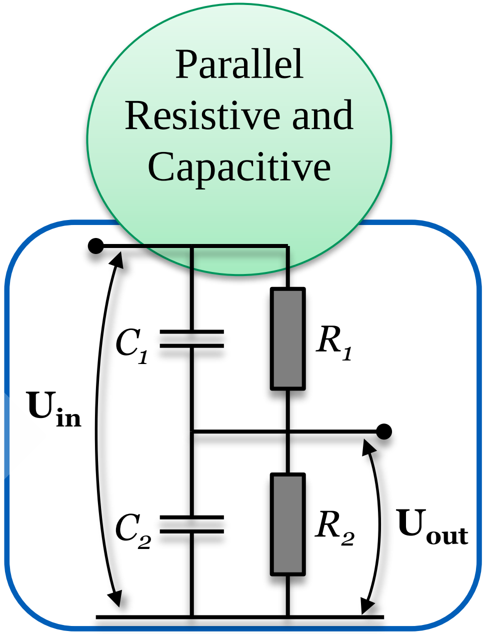
- Produces an output voltage that is a fraction of its input voltage.
- ***Voltage division*** refers to the partitioning of a voltage among the components of the divider.

Voltage divider









Divider Type		DC	AC	SI	LI
Resistive	*High Ohmic (MΩ)*	++	+	+	-
	Low Ohmic (kΩ)	-	-	-	++
Capacitive		--	++	++	-
Damped Capacitive		--	+	++	++
Parallel Resistive and Capacitive		+	+	+	+

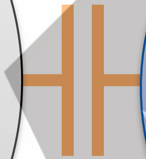
++ works well **+ works** **- problems or limitations** **-- cannot be used**

Stray Capacitance

Any two adjacent conductors can be considered a capacitor

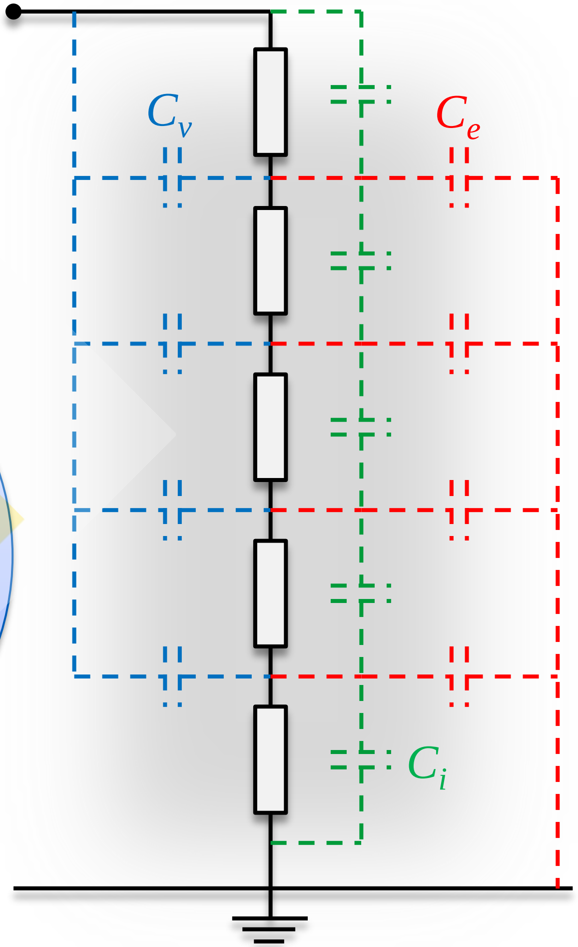
High voltage divider has an open structure

- **Stray capacitance** from objects close to the divider have an influence
- Ground, HV feeder, divider elements



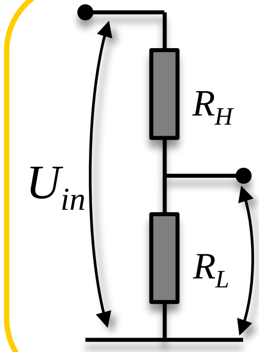
Usually these influences can not be avoided

- Correct design and selection of divider
- Pressurized gas capacitors do not have this problem (coaxial design)



Capacitive coupling of isolated systems

High Resistance Divider (mΩ)



$$U_{out} = \frac{R_L}{R_H + R_L} U_{in}$$

Optimal: **DC average value**

Also: *LI peak value, time parameters, overshoot*

(small R better for measuring LI)

Problem: **Overheating of HV resistor**

(main problem for ALL resistive dividers)

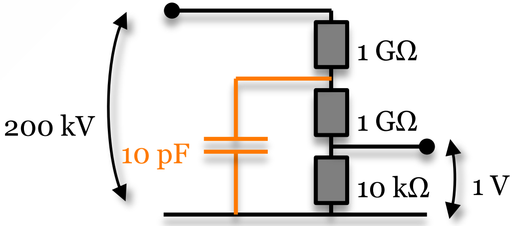
Limit $P = U^2$ / large R

(large R = better for slower pulses, DC)

Typical design: 100 µA to 1 mA [1GΩ, 100 kV = 10…100 W]

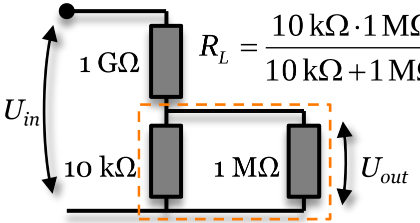
Stray Capacitance

- Stray capacitance to ground (or HV objects)
- In a 2 GΩ divider for measurement of 200 kV a stray capacitance of 10 pF forms a low pass filter
  - Filter attenuates fluctuations and restricts measurement speed (τ =RC)



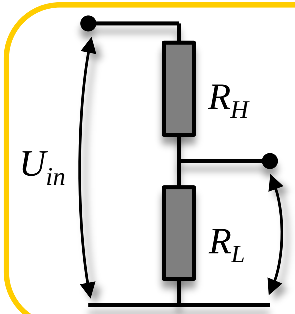
Meter Loading

The resistances of a high voltage DC divider are usually so large, that the meter input resistance (typically 1MΩ or 10MΩ, sometimes 10 GΩ) has an influence (changes divider ratio)



$$R_L = \frac{10\,\text{k}\Omega \cdot 1\,\text{M}\Omega}{10\,\text{k}\Omega + 1\,\text{M}\Omega} = 9.99\,\text{k}\Omega$$

LOW Resistance Divider (kΩ)



$$U_{out} = \frac{R_L}{R_H + R_L} U_{in}$$

Optimal: **Lightning Impulses (LI)**
– faster (shorter) impulses

Problem: **Stray Capacitance** of high voltage resistor

High voltage resistance typically 1 kΩ to 20 kΩ

The resistors absorb the energy of the impulse

Needs time to cool down between impulses

$$\text{Energy} = P \cdot t$$

E.g.

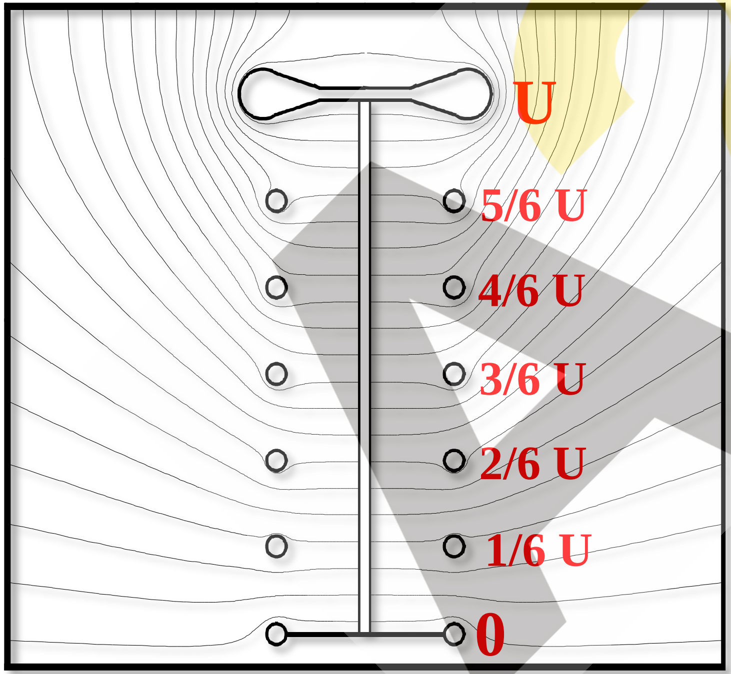
LI: 1.2/50 pulse duration ≈ 100 – 200 µs
SI: 250/2500 pulse duration ≈ 5 – 10 ms

$t_{SI} >> t_{LI}$ ⇨ *SI has too much energy =* ***overheating***

Field Grading

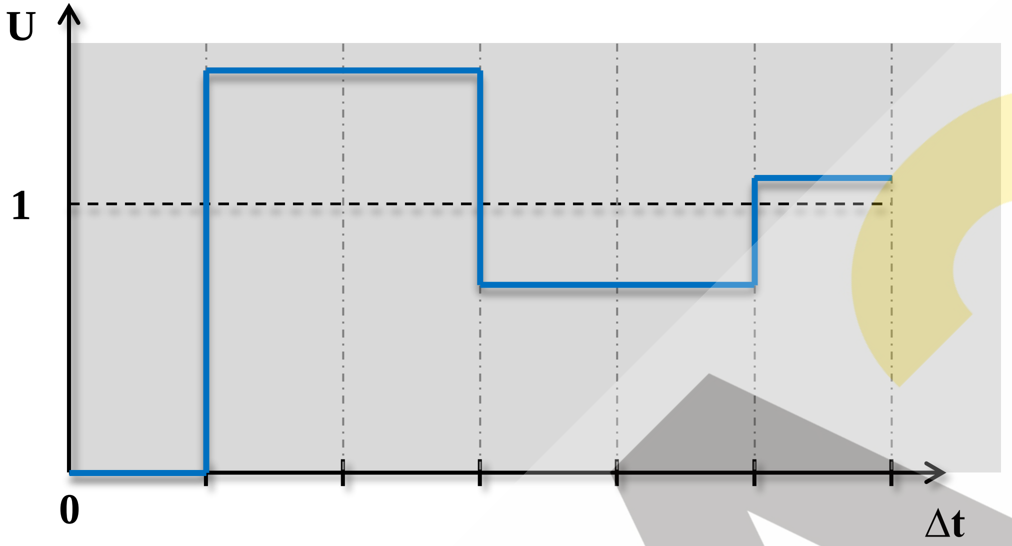
In order to avoid low pass filtering effect, the field along the high voltage resistor must be matched with the resistance distribution

- *Using a shield or guard ring placed over a resistive divider to enforce a uniform field*



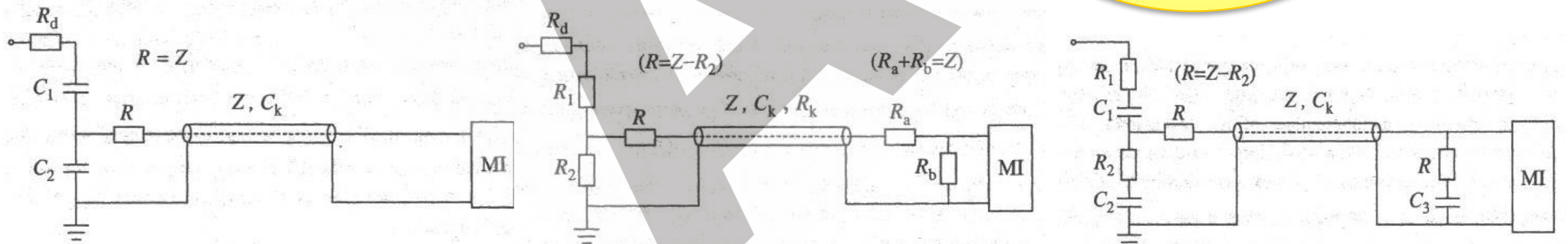
An alternative is to make non-linear resistance distribution according to the field

Measurement Cable



If the measurement cable is not matched with the instruments ($Z_1 \neq Z_2$), the signal will be reflected many times before it settles.

- Speed of light c = 30 cm/ns
- Velocity of signal in cable v = 77% (~ 23 cm/ns)
- 20 m cable $\Delta t \approx 87$ ns



$(C_3 = C_1 + C_2 - C_k)$

Recording Instruments

Resolution

- The resolution (8bits) of standard oscilloscopes is the minimum that can be accepted for impulse measurements.
- Often higher resolution (10 or 12 bits) is needed to detect changes when the test results are analyzed.

Bandwidth

- Bandwidth has to be >25 MHz.
- Settling of the step response is critical.

Input voltage level

- The signal in the cable for high voltage laboratory measurements is hundreds of volts. Signal to noise ratio is not high enough for lower signal levels.
- Good input attenuators are needed.

Software

- Special software is needed for evaluation of impulse parameters.

Current Measurements

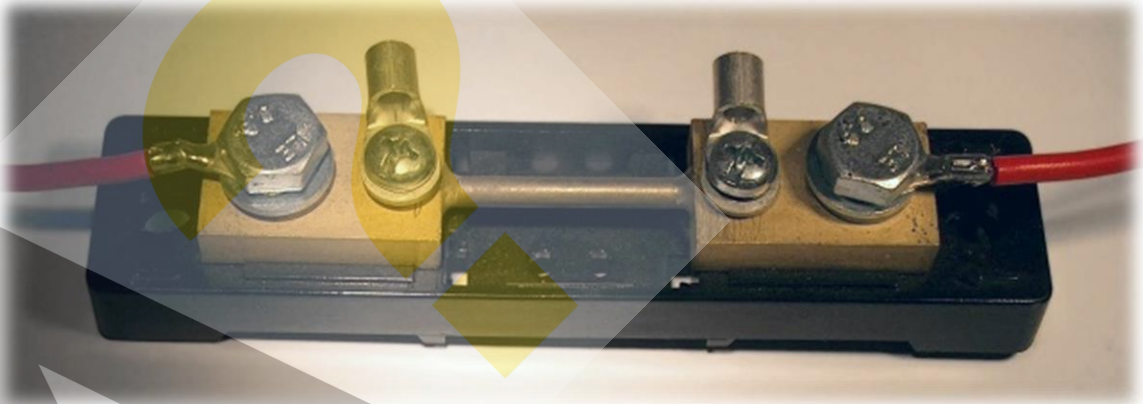
- Shunts
  - Rogowski Coil

Current Measurements

Small DC measured using **multimeter** *(volt-ohm-millammeter)*

Large currents measured using a ***shunt***

- A resistor of accurately known resistance (shunt) is placed in series with the load so that nearly all of the current to be measured will flow through it.
- The voltage drop across the shunt is proportional to the current flowing through it
  - Since its resistance is known, a voltmeter connected across the shunt can be scaled to directly read the current value.

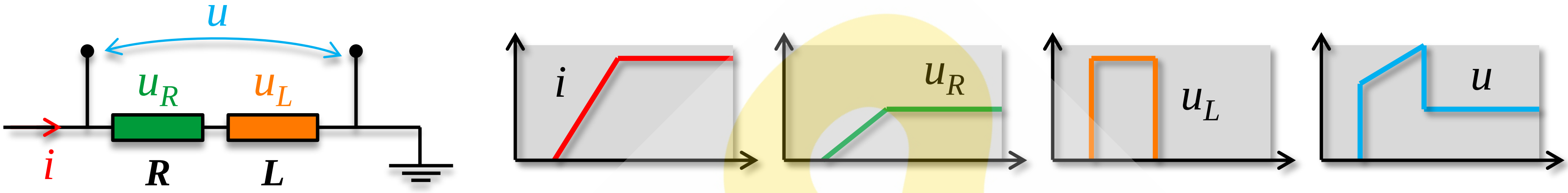


AC measured using a current transformer, shunt, or **Rogowksi coil**

Surge current typically measured using a shunt *(Rogowski coil also applicable)*

Current Shunts

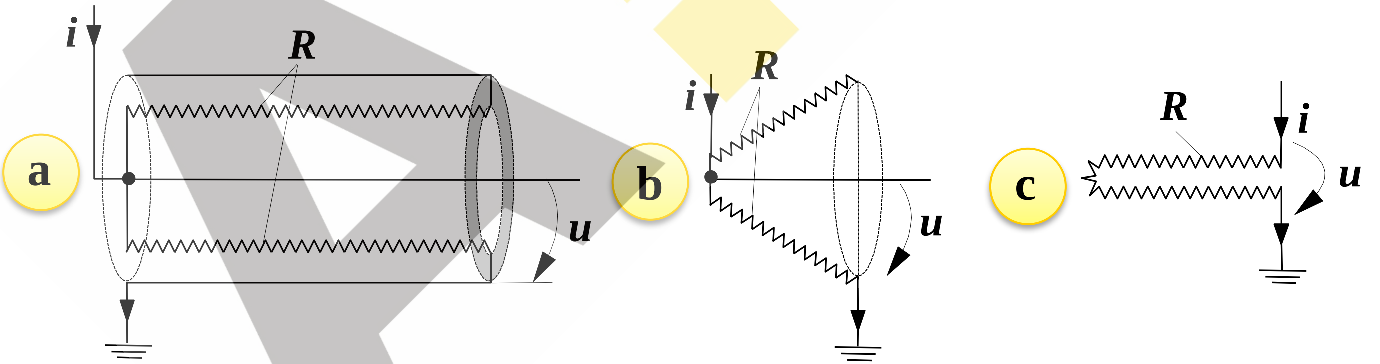
Inductance of resistor has a significant role on measurements



- ➢ Inductance is minimized by ensuring that the magnetic fields of the conducting paths cancel each other out

Shunt designs can be:

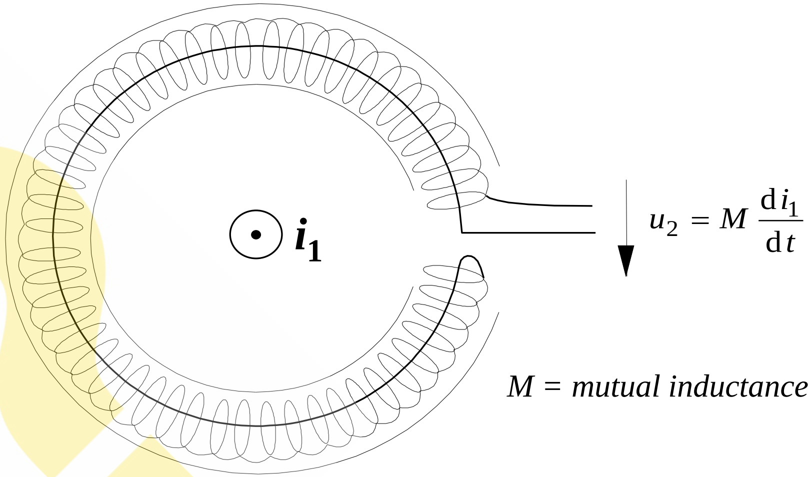
- **Coaxial** (a)
- **Radial** (b)
  - or otherwise symmetrical structure. e.g. **loop** (c)



Structures are designed to improve cooling, compensate magnetic field and minimize inductance.

Rogowski Coil

- ⇨ Air-core, symmetrical toroid shaped coil
- ⇨ Used as **current transformer** to measure current of a conductor passed through the coil
  - Dynamic properties depend on mechanical structure and winding design
  - To minimize stray inductance, coil is wound tightly, symmetrically and perpendicular relative to the tube

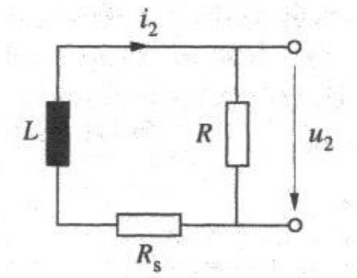


$u_2 = M \frac{di_1}{dt}$

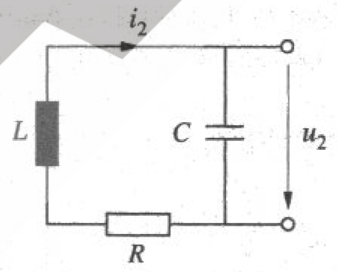
M = mutual inductance

- ⇨ Secondary voltage u_2 is proportional to measured current
  - **Integrating circuit** needed to define ratio:

Add small resistor R to secondary coil *Add large resistor R and capacitor C as integrator*

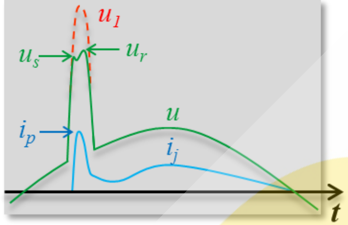


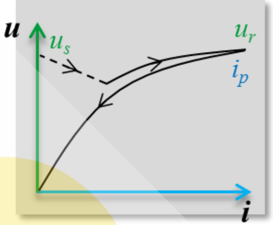
$$u_2 = Ri_2 = \frac{R}{L}\int M \frac{di_1}{dt}dt$$



$$u_2 = \frac{1}{RC}\int M \frac{di_1}{dt}dt$$

Summary





Insulation coordination:

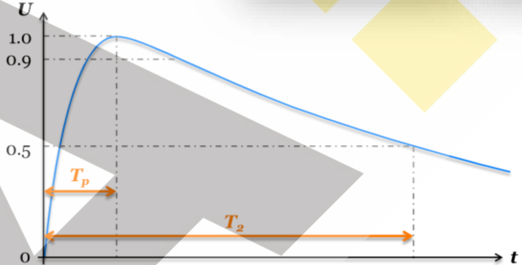
- Surge arrestors
  - placement
- Spark gaps

Testing

- Purpose, types, requirements, standards

Test voltages

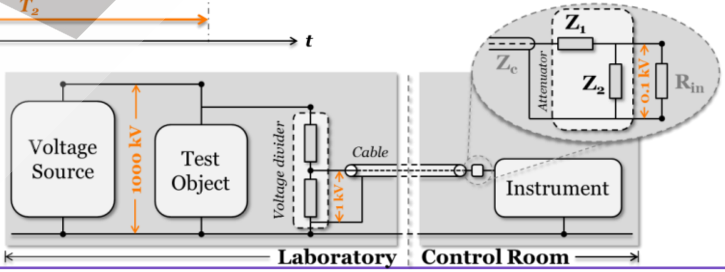
- Standard AC, DC, SI, LI



Testing vs. diagnostics

Measurement systems

- Setup and components
- Voltage dividers
- Current measurements



Thanks!