High voltage engineering

Overvoltages

- power frequency
- switching surges
- lightning surges

Overvoltage protection

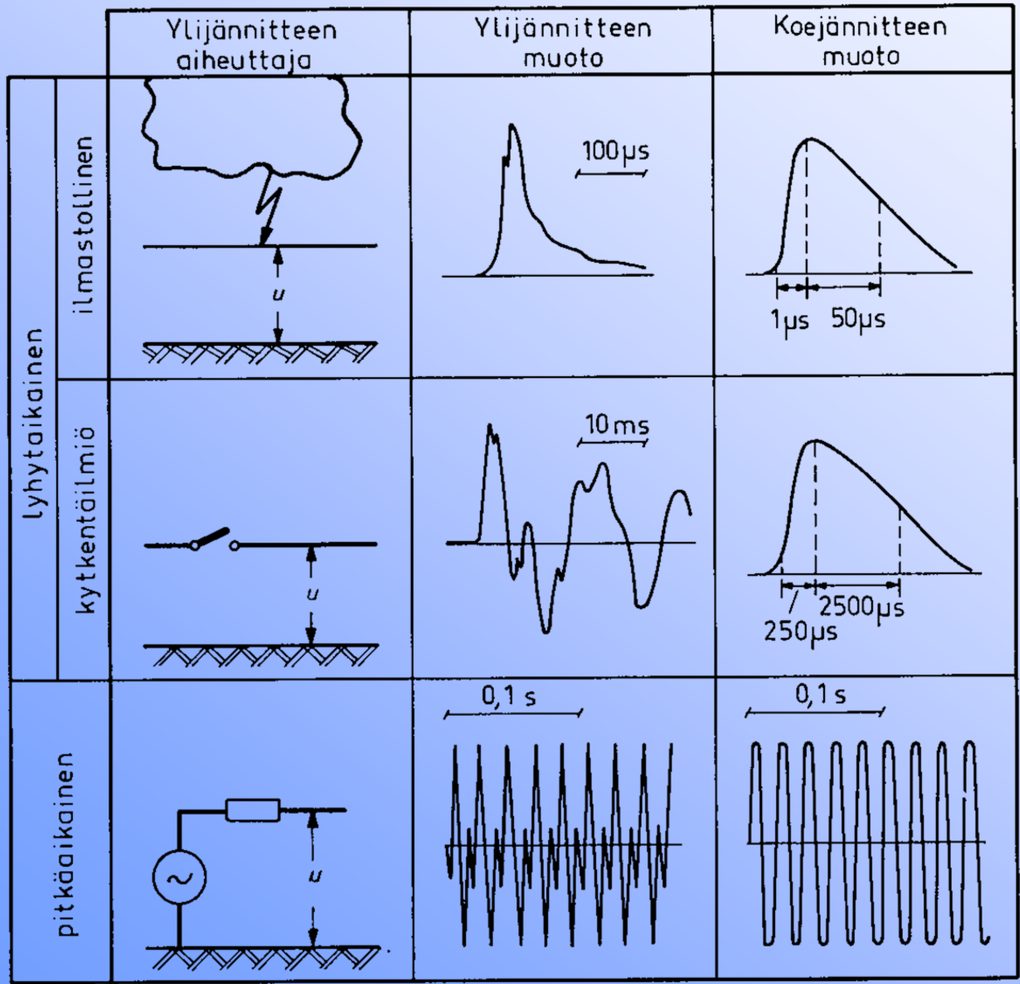
- earth wires
- spark gaps
- surge arresters

Insulation coordination

Overvoltages

- power frequency
- switching –
- lightning –

Short time ($> U_m\sqrt{2}$)



Ylijännitelajit

Lightning

Switching

Power frequency

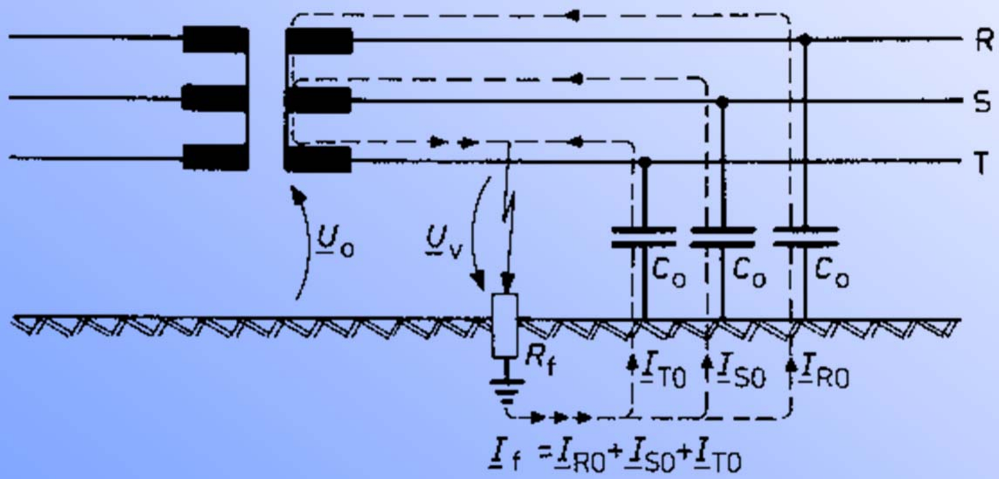
Power frequency overvoltages

- earth faults in unearthed & compensated neutral systems

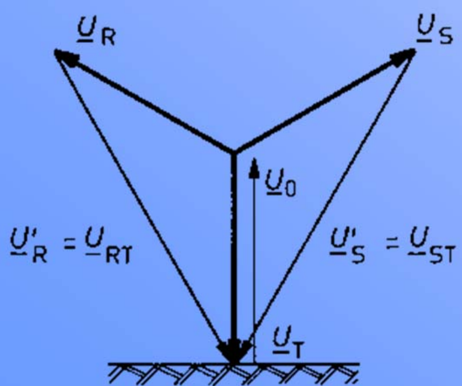
⇒ maximum phase voltage

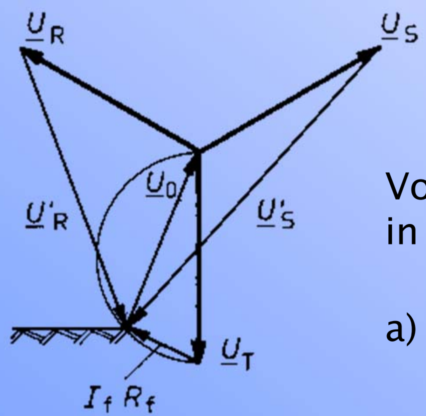
$\approx 1{,}05 \cdot \sqrt{3}\, U_V$

U_v is the normal phase voltage



Flow of fault current in an earth fault in unearthed power system.
U_v = phase voltage before fault.
R_f = fault resistance.





Voltages during an earth fault in unearthed power system.

a) $R_f = 0$, b) $R_f \neq 0$, $U'_{max} \approx 1{,}05 \cdot \sqrt{3}\, U_v$

Limiting the earth fault voltages

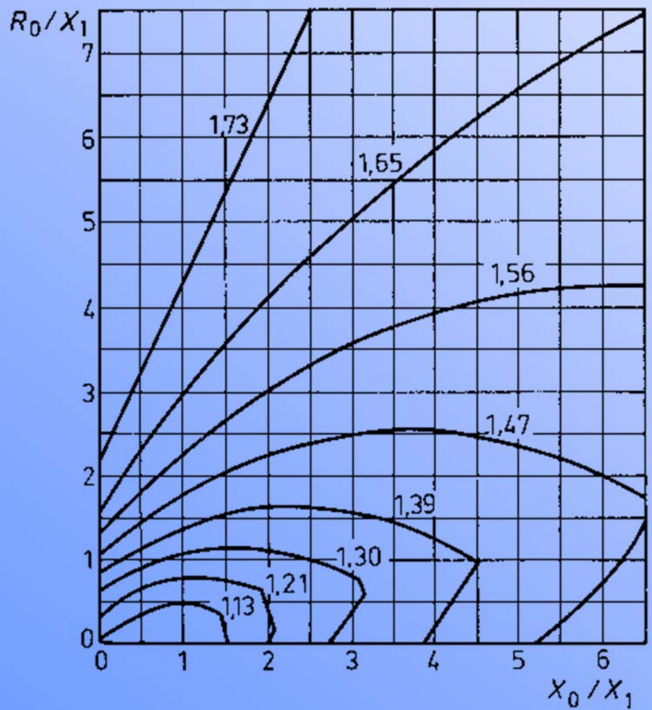
Solid earthing; earth fault factor $k \le 1{,}4$

$$k = \frac{U_T}{U_V} = \frac{\text{Highest phase voltage (fault)}}{\text{Normal phase voltage}}$$

$$k \le 1{,}4 \quad \text{if}$$

$$\begin{cases} X_0 / X_1 \le 4{,}5 \\ R_0 / X_1 \le 1{,}0 \end{cases}$$

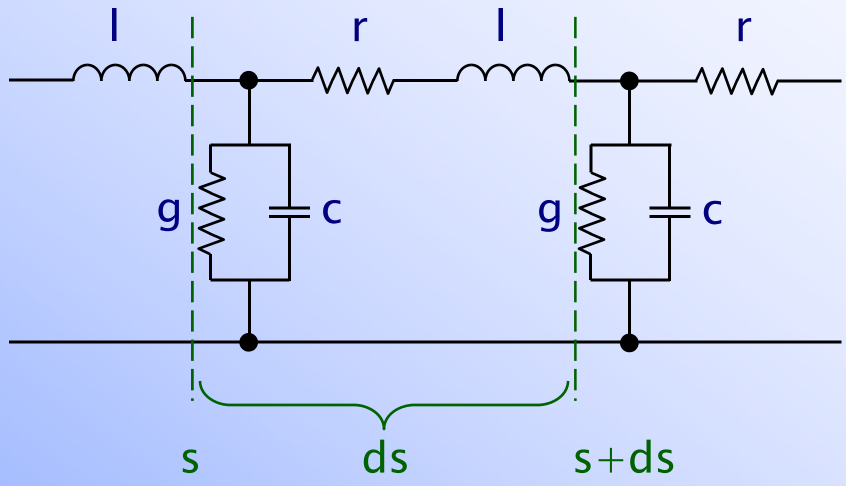
In Finland the 420 kV system is solid earthed



Values of k, when $R_1 = R_2 = 0{,}1\ X_1$

Power frequency overvoltages

Ferranti-phenomenon: in no-load state the voltage of a line rises towards the end



U_2 = voltage in the line end

U_1 = voltage in the line beginning

$$\frac{U_2}{U_1} = \frac{1}{\cos \beta\, s} \quad ; \quad s = \text{line length}, \quad \beta = \text{phase constant}$$

$$\beta = \sqrt{(r + j\omega l)(g + j\omega c)}$$

$$r \ll l \quad \& \quad g \ll c$$

$$\Rightarrow \quad \beta \approx \omega\sqrt{lc} = 6° / 100\ \text{km}$$

(regardless the voltage !!!)

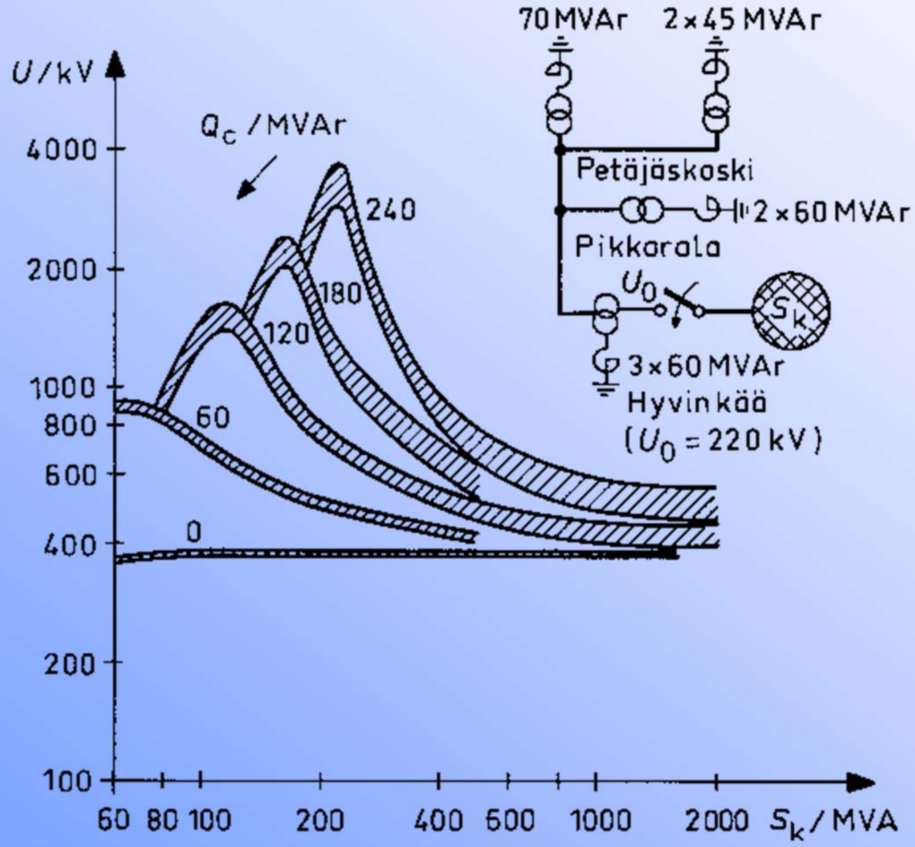
Example:

s/km	U_2/U_1
100	1,006
200	1,022
300	1,05
400	1,09
500	1,15

Energising a capacitively loaded network

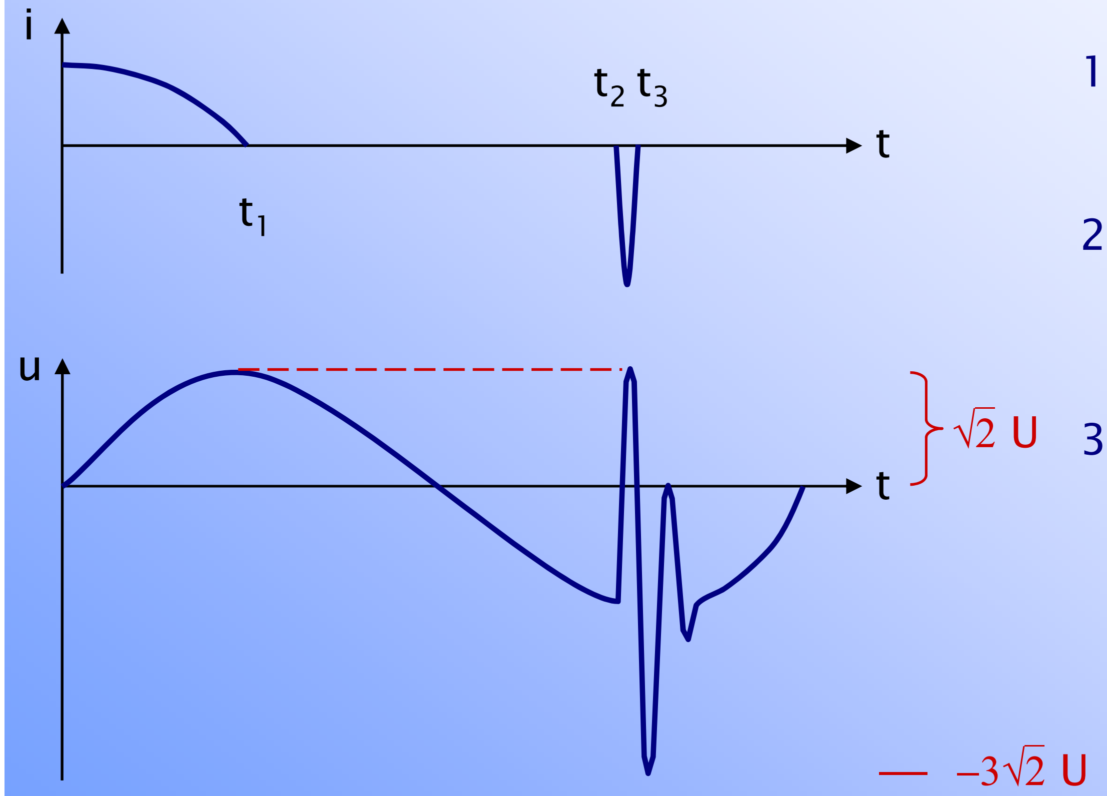
S_k = short circuit power

Q_c = capacitive var production – compensation reactor absorption



420 kV system voltages (U) as a function of feeding point short circuit power (S_k) and undercompensation degree (Q_c).

Switching overvoltages: Interrupting capacitive current



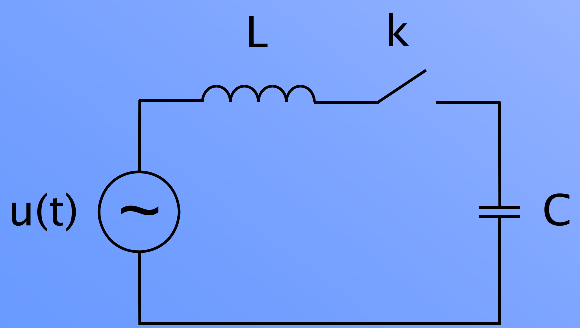
1) current of C is cut off at time t_1;
   in C it remains a $\sqrt{2}U$ voltage

2) half 50 Hz cycle later the voltage
   across k is $2\sqrt{2}U$ (t_2); restriking
   with frequency $\omega = 1/\sqrt{LC}$

3) if current interrupted 1. half cycle
   later (t_3), voltage in is C $-3\cdot\sqrt{2}U$

Means of limitation :

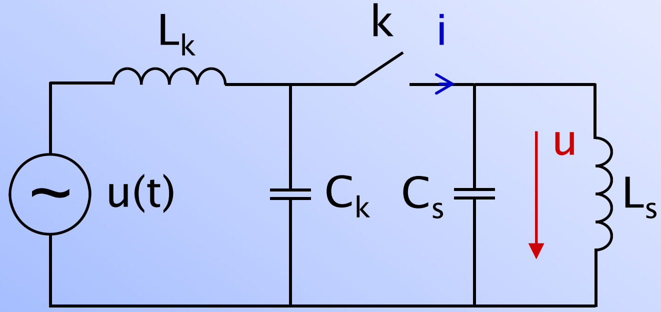
- breaker selection (no restriking)

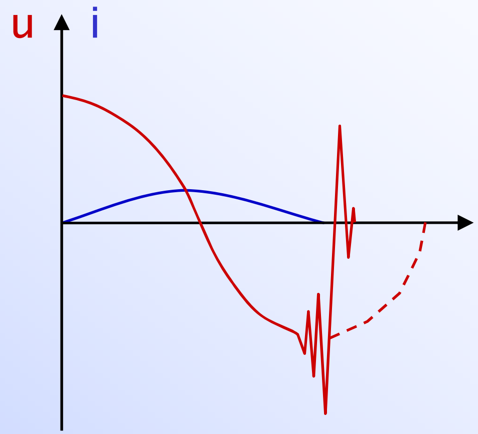


$$u(t) = \sqrt{2}\, U \sin \omega t$$

$$\left(\omega L \ll \frac{1}{\omega C} \right)$$

Interrupting a small inductive current





$$u(t) = \sqrt{2}\, U \cos \omega t$$

After interruption the circuit behind k starts to oscillate with frequency:

$$\omega_S = 1/\sqrt{L_S C_S}$$

⇒ over voltage

Energy stored in L and C :

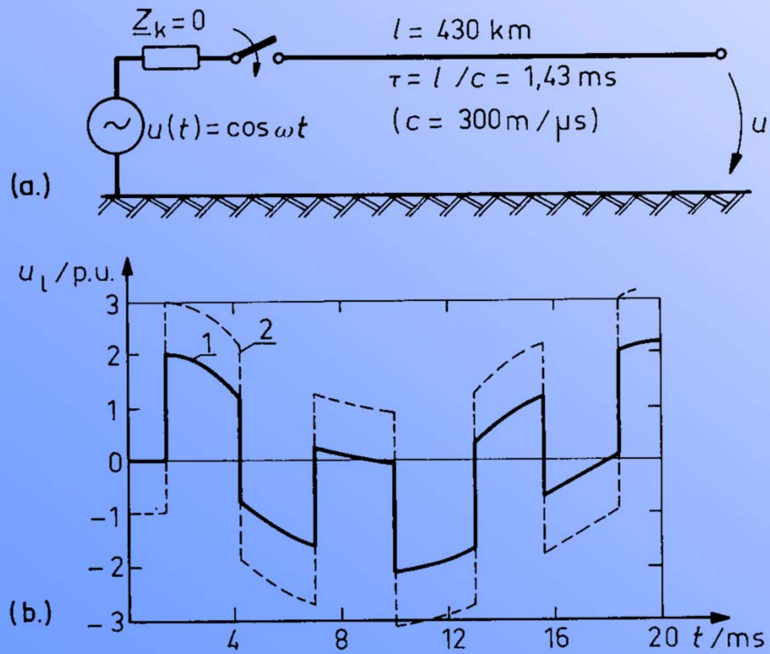
$$W = \frac{1}{2} C_S u_0^{\,2} + \frac{1}{2} L_S i_0^{\,2} = \frac{1}{2} C_S u_{L,\,max}^2$$

Means of limitation :

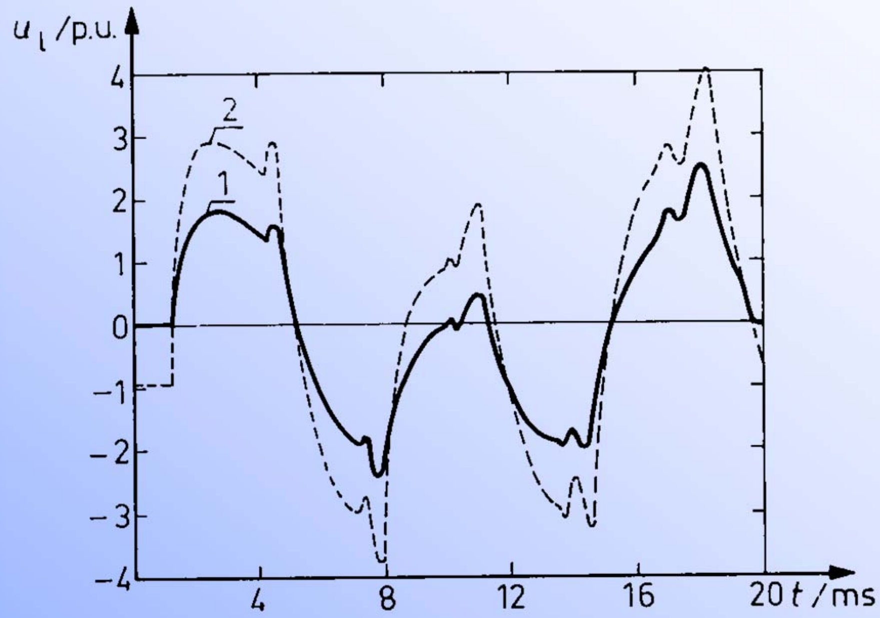
- breaker selection (restriking is Ok)
- opening resistors in CB
- increasing capacitance C_s
- surge arresters

Switching an unloaded line

- Travelling wave phenomenon
- Of importance for lines over 300 kV
- High speed reclosing & residual charge
- Highest overvoltages even 3.5 p.u.
- Mitigation : closing resistors ⇒ 2 p.u.



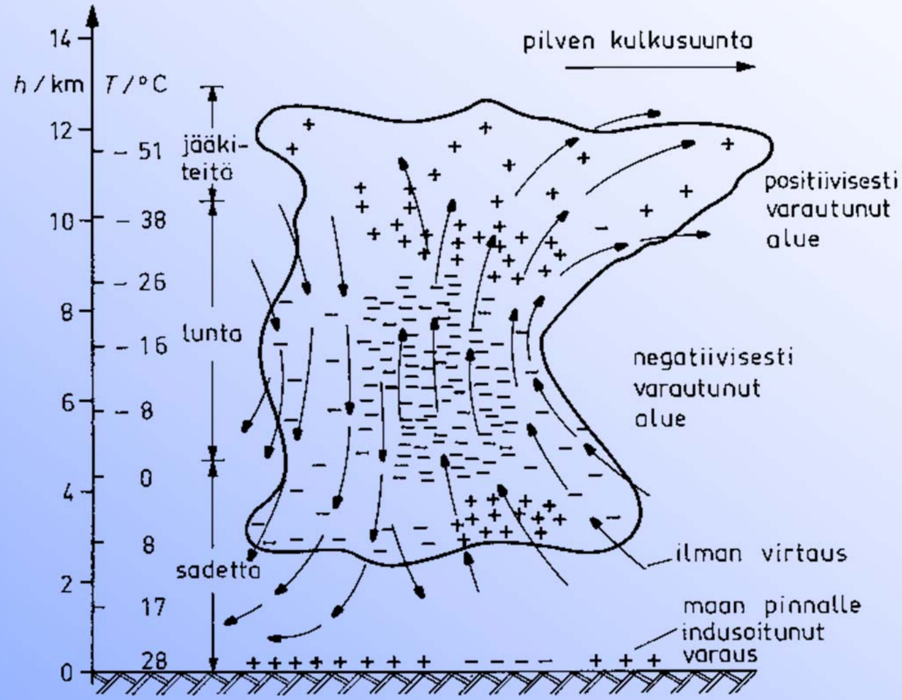
Voltage in line end when switching an unloaded line live
a) one-line diagram of the circuit,
b) voltages: graph 1: residual charge = 0
graph 2: residual charge = -1,0 p.u.



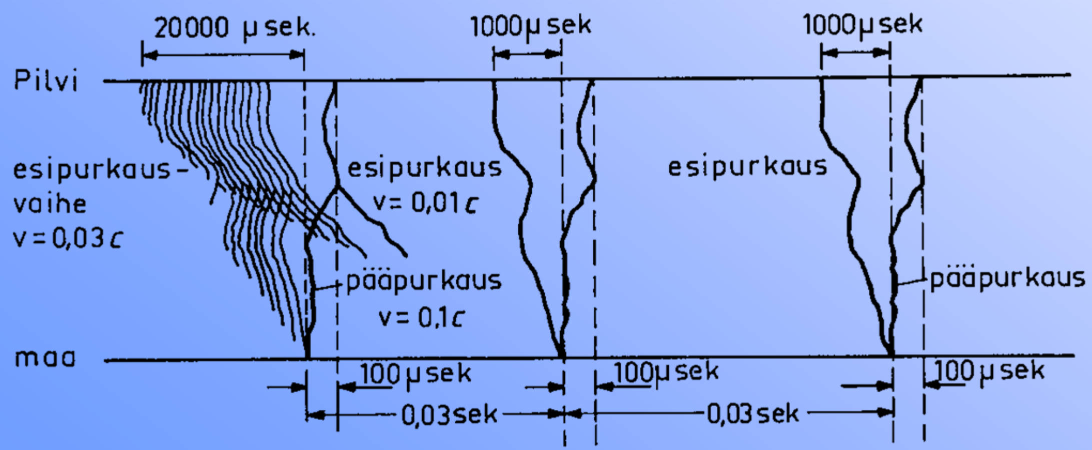
Voltage in line end when switching an unloaded line
in a strong transmission system.
graph 1: no residual charge
graph 2: residual charge -1,0 p.u.

Lightning surges

- thunder cloud and the lightning stroke

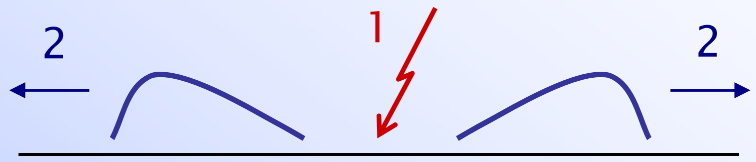


Thunder cloud cross section



Phases of a lightning stroke

Direct stroke to the conductor



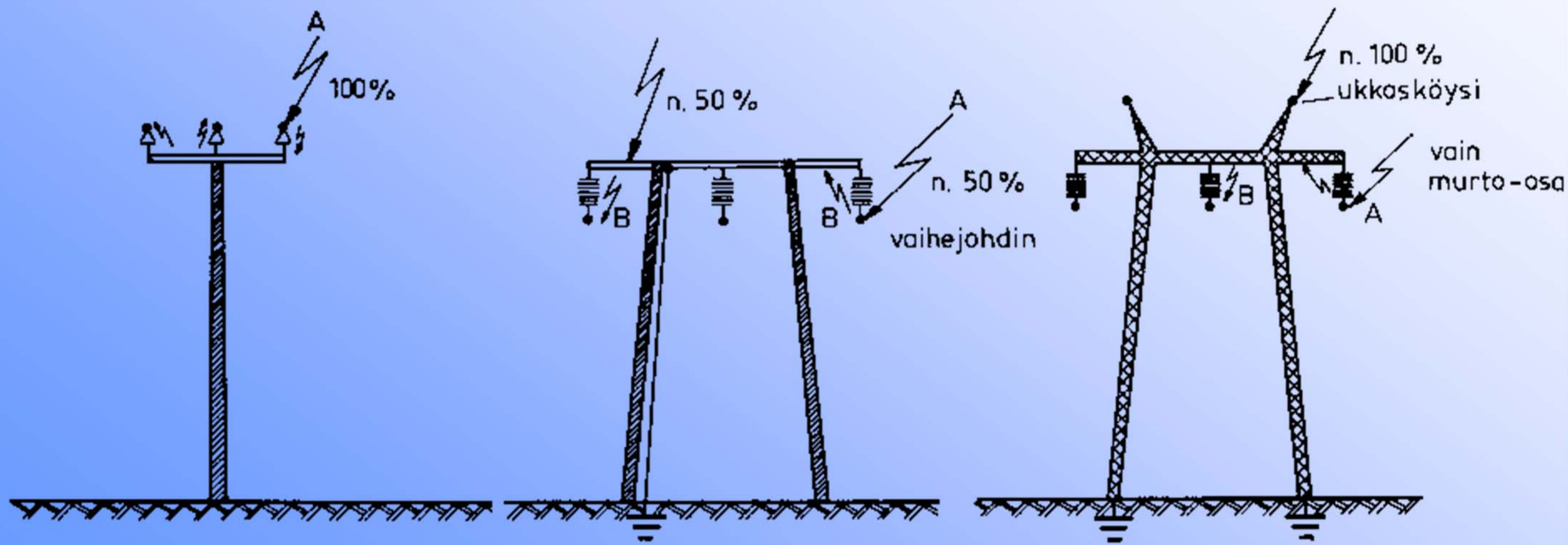
$$u = \frac{1}{2} i Z_0$$

i = lightning current, Ex. 20 kA

Z_0 = surge impedance, Ex. 450 Ω

$\Rightarrow$ u ≈ 4,5 MV

$\Rightarrow$ always causes flashover



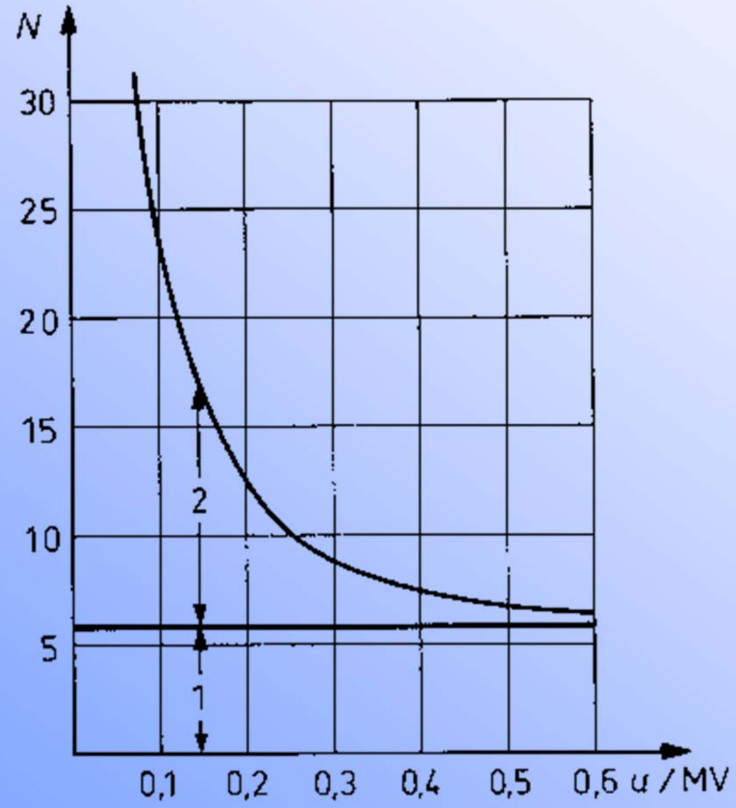
Cross-arm unearthed (wood pole)
Lightning stroke causes 3-ph fault

Cross-arm earthed
Bach flashover

Earthed pole with
shielding wires

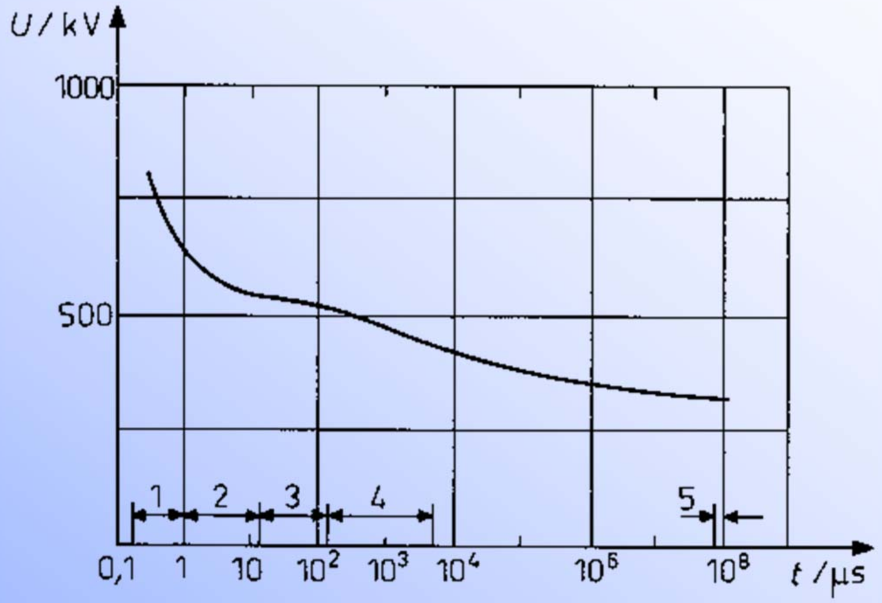
Induced overvoltages

- stroke to the line vicinity
- 3-pole travelling wave created
- U < 200…300 kV
- problem mainly in MV networks



Number of faults / 100 km, yr caused by lightning strokes for lines
Without shielding wires. 1 direct strokes, 2 induced overvoltages.

Means for limiting the overvoltages



Voltage withstand curve of a 123 kV transformer. 1: steep surges, 2: slow surges, 3: “short” switching and, 4: “long” switching over voltages, 5: 50 Hz voltage, (1 min)

- circuit breaker selection
- closing / opening resistors
- parallel reactors
- protection capacitors
- shielding wires
- spark gaps
- surge arresters

Shielding wires

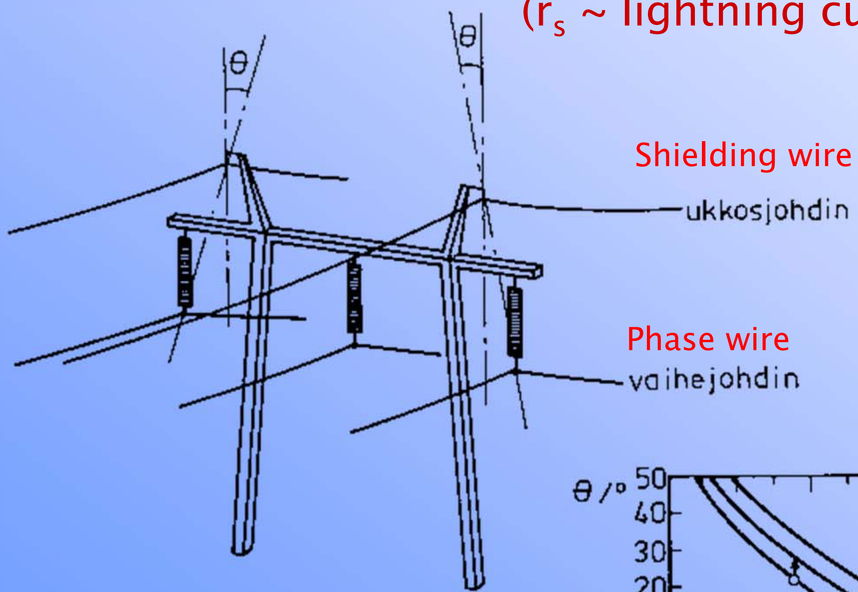
- used for 110 kV, 220 kV, 400 kV lines
- In 110 kV lines the number of lightning faults 7-fold in no shielding wires
- shielding angle θ selected such that the currents with stroke distance higher than r_s can not reach the phase conductors

(r_s ~ lightning current)

$r_s \approx 6{,}7\ i_s^{0{,}8}$

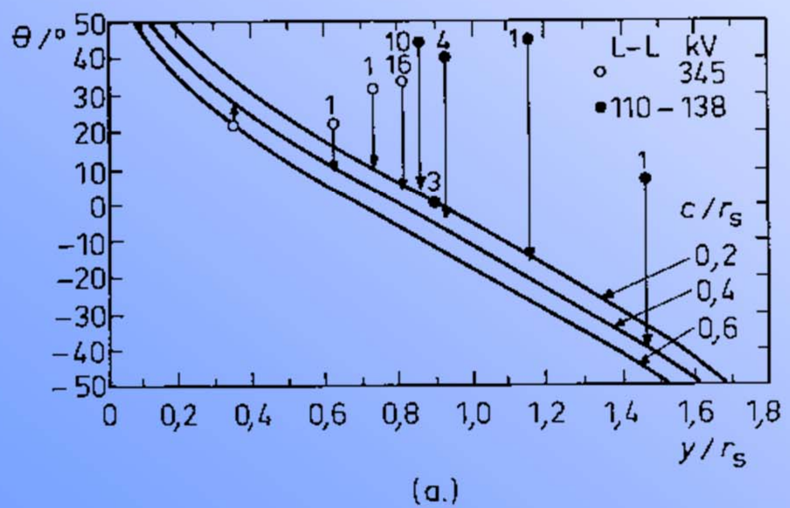
Ex. 20 kA

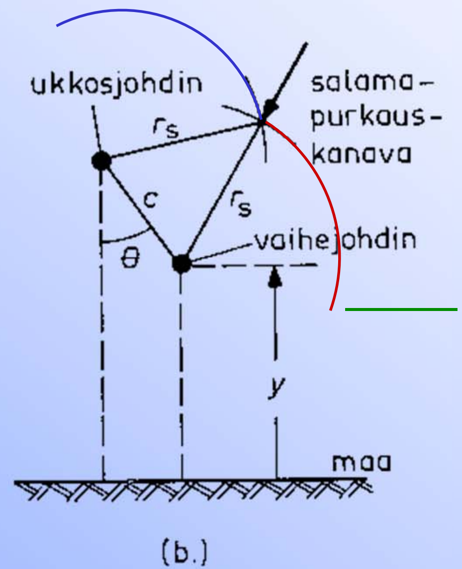
$\Rightarrow$ 74 m



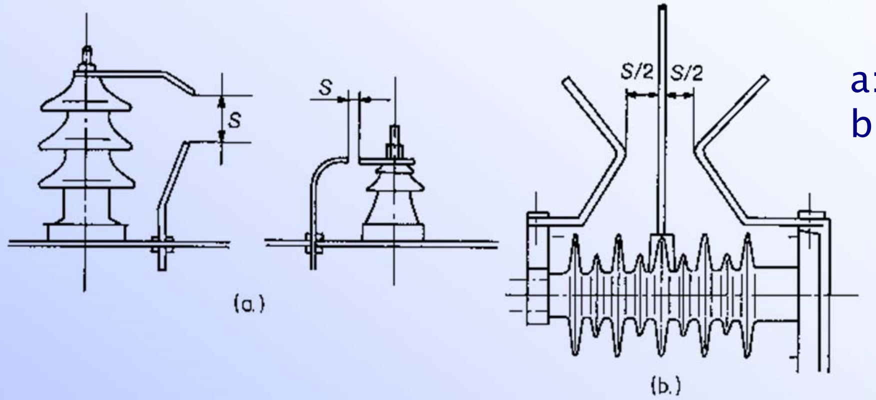
The shielding angle θ

The dependence of shielding angle on the line geometry. $r_s \triangleq$ stroke distance





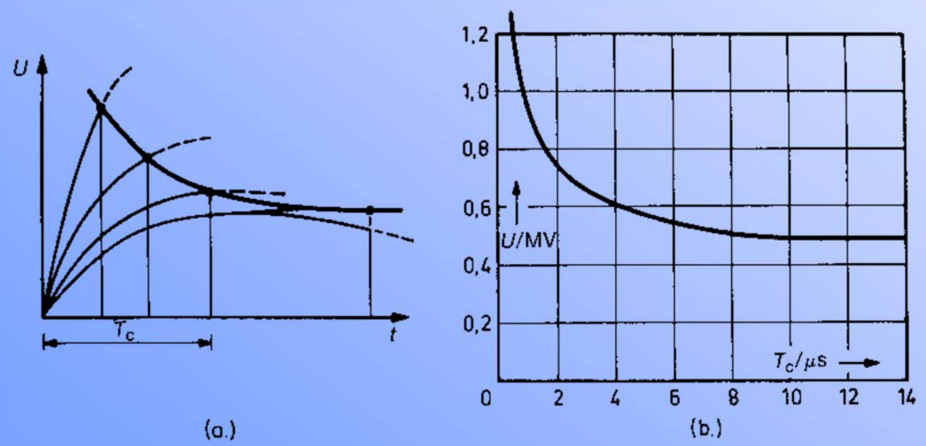
Spark gaps



a: s=80 mm or 100 mm
b: s=60 mm or 80 mm

Sparks gaps used for pole mounted secondary transformers

- used for < 200 kVA pole transformers
- operation causes an earth fault ⇒ reclosing
- when operates, the surge voltage collapses
  ⇒ transformer must be tested for a cut surge
- large variation in the flashover voltage
- with steep surges, the flashover voltage strongly increased

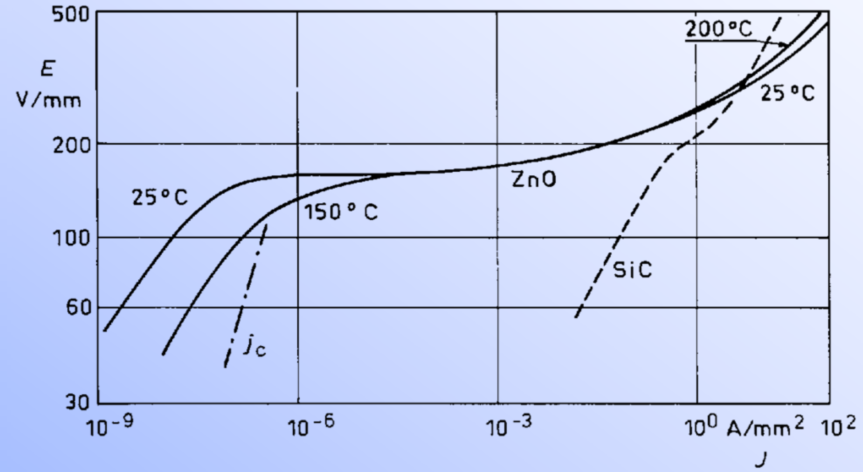


Voltage-time characteristics for lightning surges. a) estimation method,
b) results for a 30 inch spark gap (positive polarity)

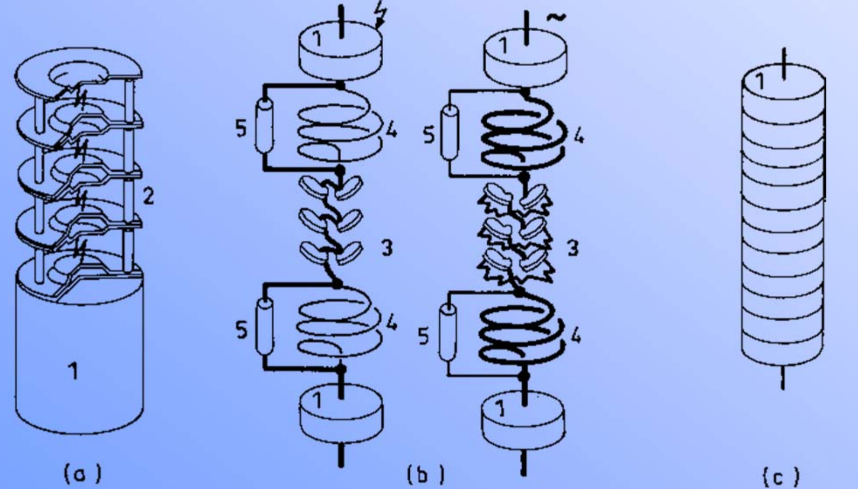
Surge arresters

Two types:

- spark gaps in series with SiC-resistors
- ZnO - surge arresters



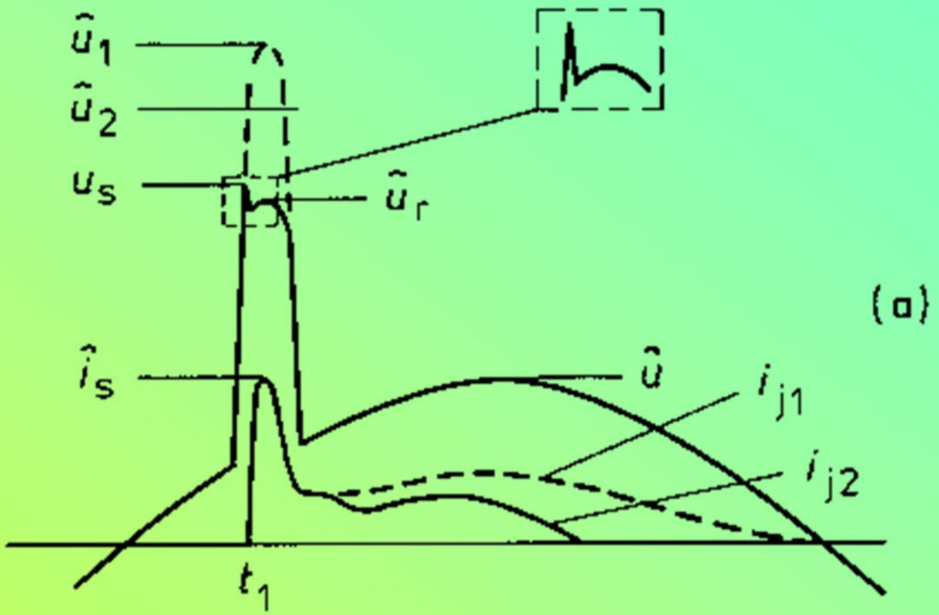
Voltage - current characteristics of SiC and ZnO resistors



Surge arrester types. (a) spark gap type, (b) active spark gap type, (c) ZnO - type.
1 = resistor, 2 = spark gap, 3 = active spark gap, 4 = blowing coil, 5 = by-pass resistor.

The operation of a surge arrester

SiC

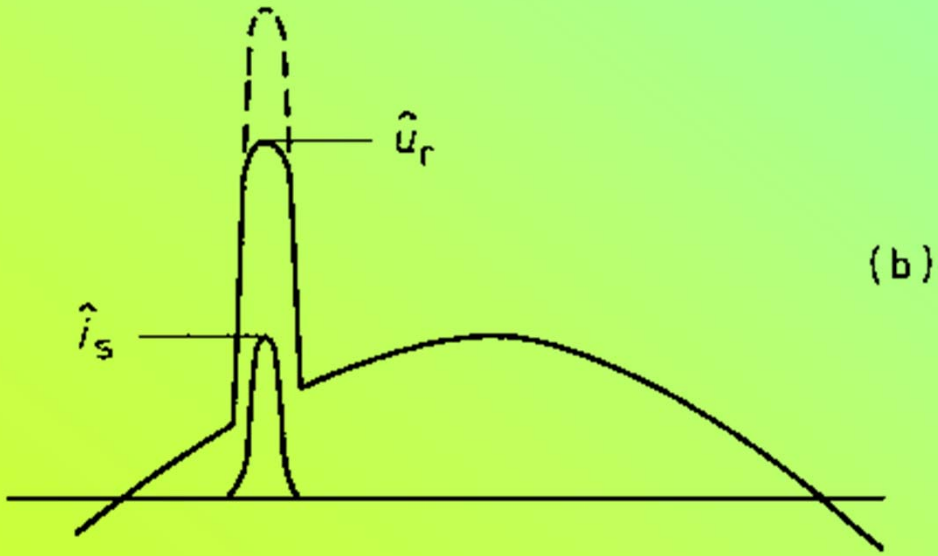


- $\hat{u}_1$ = peak value of the incoming voltage
- $\hat{u}_2$ = insulation level of the equipment
- u_s = break down voltage (SiC only)
- $\hat{u}_r$ = remaining voltage of the arrester
- $\hat{u}$ = peak value of 50 Hz voltage

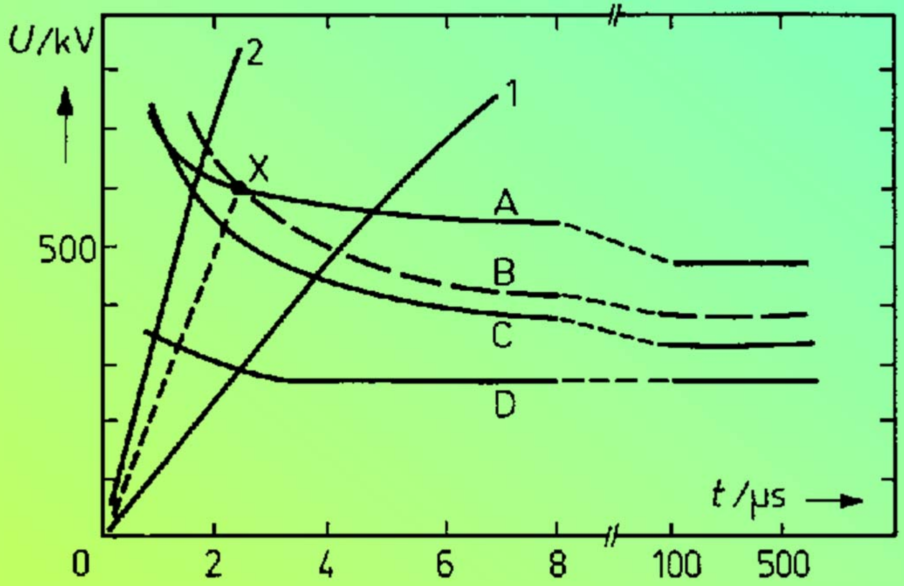
- $\hat{i}_s$ = peak value of the surge current
- $\hat{i}_{j1}$ = 50 Hz current in the spark gap
- $\hat{i}_{j2}$ = 50 Hz current in the active spark gap

- t_1 = time of break down

ZnO

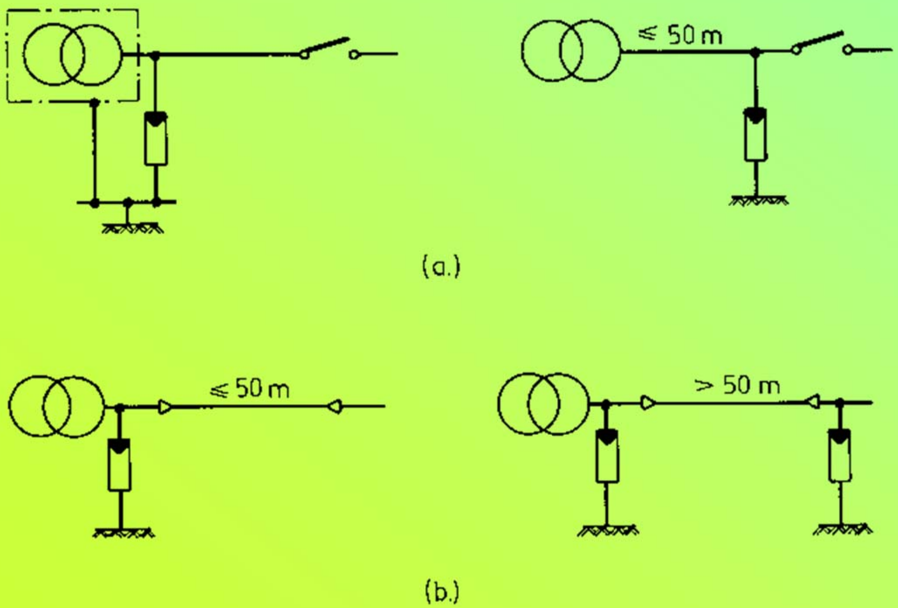


Transformer protection using spark gap or surge arrester



A ≙ a transformer, voltage strength for surges 550 kV, B ≙ spark gap S = 79 cm, C ≙ spark gap S = 66 cm, D ≙ surge arrester U_N = 120 kV, 1,2 ≙ test voltage crest values

Surge arrester location



a) transformer connected in overhead line
b) transformer connected in underground cable

Rated data of a surge arrester

Protective level: highest voltage over the surge arrester. Withstand level voltage of the power system equipment must be 1,2 -1,4 * protective level.

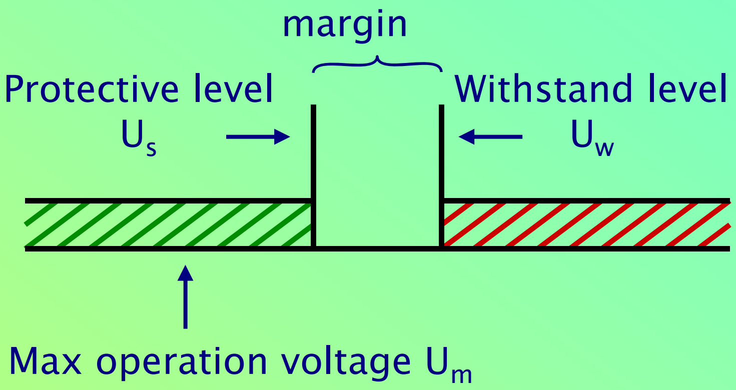
Nominal voltage: highest voltage that the surge arrester can take without break down. Must be 5…10 % higher than maximum expected operation voltage of the power system considered.

Nominal discharge current: current surge amplitude, that corresponds to the protective level. Standard values: 20, 10, 5, 2.5 kA

Rated current: the capacity to discharge energy

Insulation coordination

Fitting the insulation level and the protective level together



U_w vs. U_m

U_w = withstand level =

margin
- lightning surges 1.2 – 1.4
- switching overvoltages 1.1 – 1.2

- the ratio of protective level and operation voltage
  - in conventional surge arresters about 2.4
- margin for surge arrester operation 10 %
- earth fault factor k
- highest normal operation voltage as phase voltage

Example. Unearthed system $U_m = 24$ kV

- earth fault factor $k = 1.05 \cdot \sqrt{3} \approx 1.82$
- margin for surge arrester operation 1.1
- protective level / operation voltage 2.4
- margin between insulation level and protection level 1.4

Insulation withstand level:

$$U_w = 1.82 \cdot 1.1 \cdot 2.4 \cdot 1.4 \frac{U_m}{\sqrt{3}}$$

$$= 93.2 \text{ kV}$$

(Std IEC–71: 95 kV)

Example: Solid earthed system $U_m = 420$ kV

- earth fault factor	k = 1.4
- margin for surge arrester operation	10 %
- protection level / operation voltage	2.4
- margin between insulation level and protection level	1.2

Insulation withstand voltage:

$$U_w = 1.4 \cdot 1.1 \cdot 2.4 \cdot 1.2 \frac{U_m}{\sqrt{3}}$$

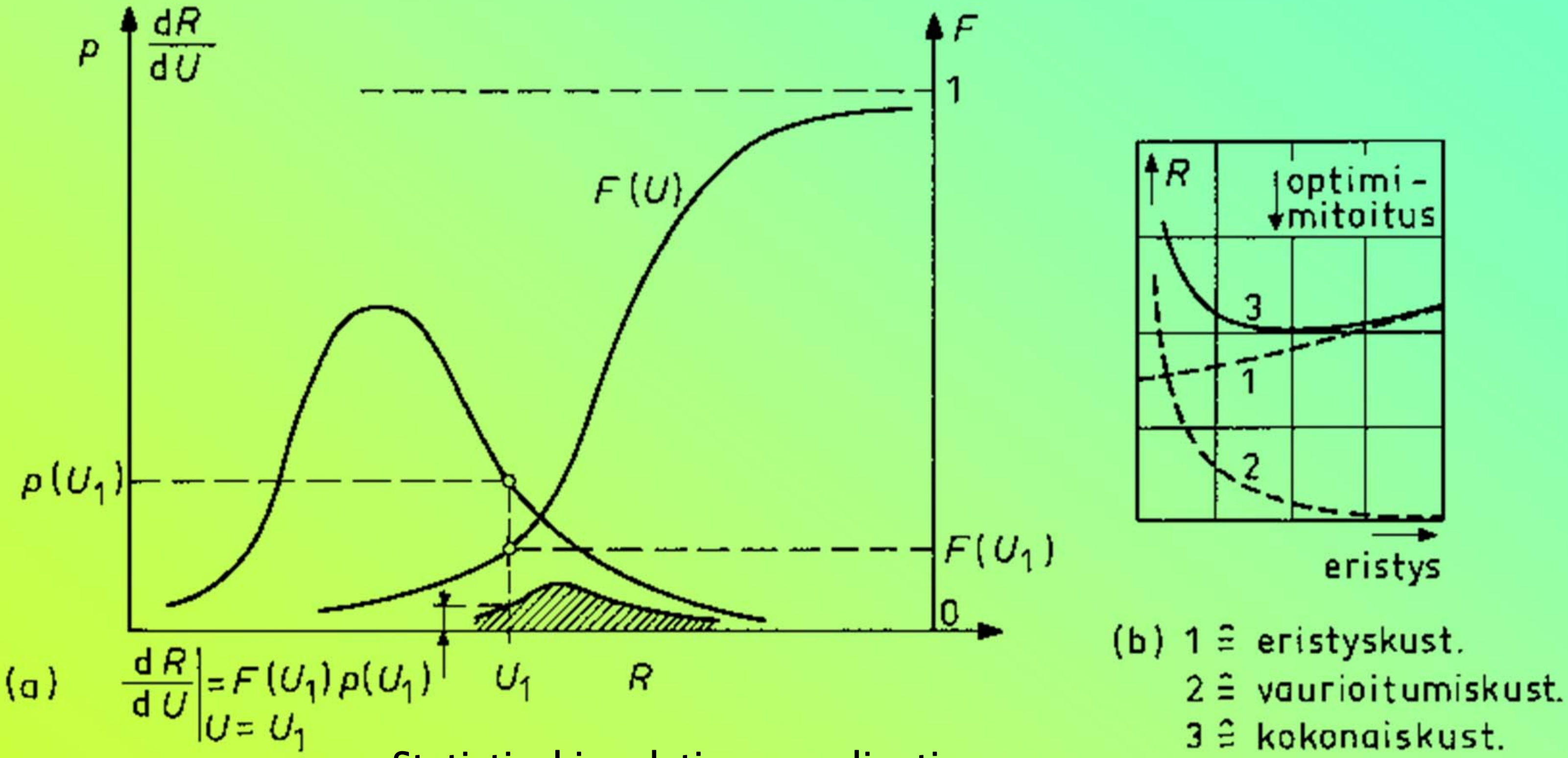
$$= 1075 \text{ kV}$$

(Std IEC-71: 1050 kV tai 1175 kV)

Statistical methods

$$\text{Failure risk: } R = \int_{U_{min}}^{U_{max}} p(U)\,F(U)\,dU$$

- p(U) is the distribution of the voltage stresses
- F(U) is the probability function of insulation strength

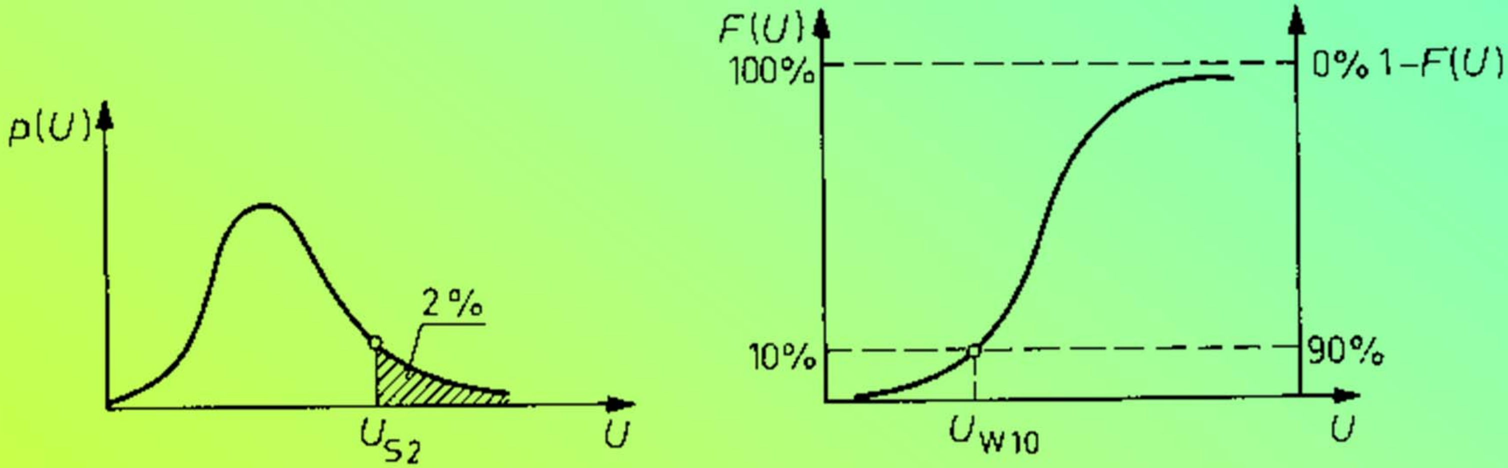


Statistical insulation coordination.
a) the risk of failure, b) the minimum of costs
1= insulation costs, 2=failure costs, 3=total costs

Statistical safety factor γ

$$\gamma = \frac{U_{W10}}{U_{S2}}$$

- U_{W10} is the voltage level with a 10 % break down probability
- U_{S2} is the voltage stress having a 2 % exceeding probability



The definition of the variables in statistical safety factor definition