HIGH VOLTAGE ENGINEERING

Electric discharges in electric power engineering

Corona discharge

- There is suddenly an overall flashover between electrodes in a uniform electric field
- In case of nonuniform configurations, the visible and audible effects of partial discharges occure before overall flashover
- These partial discharges are known as Corona discharges

Corona influence to overhead lines

- Corona creates active losses on overhead lines
- Corona losses strongly depends on ambient conditions (temperature, pressure, humidity,...)
- Precise calculation is very difficult, there are many approaches based on empirical equations derived from laboratory experiments

Calculation of Corona losses

- Peek's formula

$$P = \frac{241}{\delta}(f + 25)\sqrt{\frac{r}{D}}(U - U_0)^2 10^{-5}\ [kW/km]$$

where δ is relative air density, f is frequency, r is conductor diameter, D is axial distance of conductors, U is applied voltage on conductor and U_0 is corona onset voltage, when the voltage U_0 causes the electric field E_0 on the surface of the conductor:

$$E_0 = 21{,}2\delta m_1 m_2\ [kV/cm]$$

where m_1 is the factor respecting influence of a conductor surface pollution and m_2 is the factor respecting an influence of the weather

Calculation of Corona losses

- A.M. Zalessky's formula

$$P = 2{,}22\frac{\left(f+\frac{65}{D}\right)(U-U_0)^2 10^{-4}}{Ln\left(\frac{s}{R_{stř}}\right)}\ [kW/km]$$

where

$$R_{stř} = 19\sqrt{\frac{rE_v}{f}}\,[cm], E_v = 21{,}2m\delta\left(1+\frac{0{,}301}{\sqrt{r\delta}}\right)\ [kV/cm]$$

$$U_0 = 21{,}1m\delta\left[1+\frac{0{,}301}{\sqrt{r\delta}(1+230r^2)}\right]rLn\left(\frac{s}{r}\right)\ [kV]$$

Bundled conductors

- Electric field intensity at the distance R from a cylindrical conductor can be expressed as:

$$E = \frac{Q_1}{2\pi\varepsilon R}$$

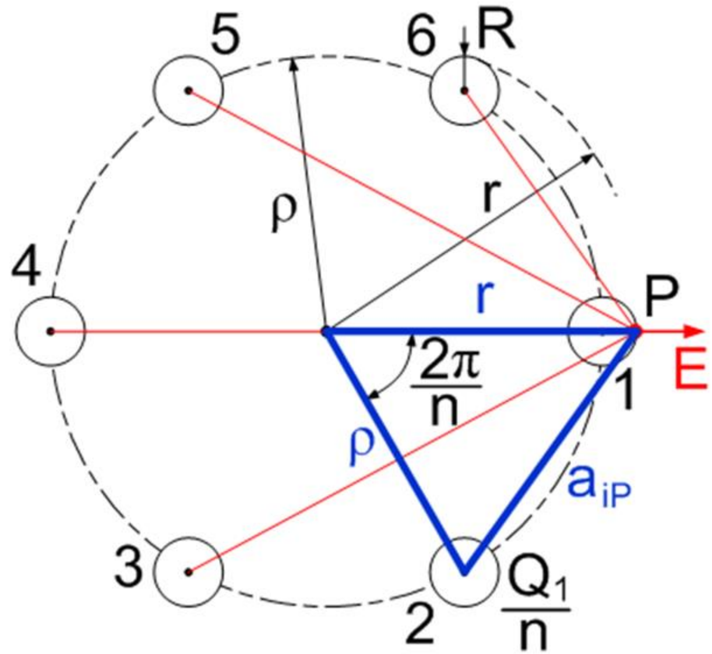
where it is assumed that the charge Q_1 is per unit length

- Elektric potential is then

$$\varphi = -\int E\, dR = -\frac{Q_1}{2\pi\varepsilon} Ln(R) + K$$

Bundled conductors

- The potential in the point P is the summ of potential contributions from all conductors in the bundle



$$\varphi_P = -\frac{Q_1}{2\pi\varepsilon n}\sum_{i=1}^{n} Ln(a_{iP}) + K$$

Bundled conductors

- Distances a_{iP} can be calculated from triangle with sides r,ρ and a_{iP} by Law of Cosines

$$a_{iP} = \sqrt{r^2 + \rho^2 - 2r\rho\, cos\left(\frac{2\pi}{n}(i-1)\right)}$$

- The maximal intensity is in the point P

$$E_{max} = E_P = -\frac{d\varphi}{dR}$$

Bundled conductors

- Differenciate the composite function, the maximal value of electric field intensity is

$$E_{max} = \frac{Q_1}{2\pi\varepsilon n}\sum_{i=1}^{n}\frac{r-\rho\cos\left(\frac{2\pi}{n}(i-1)\right)}{r^2+\rho^2-2r\rho\cos\left(\frac{2\pi}{n}(i-1)\right)}$$

- In the next, we would like to derive how is the change of maximal field intensity of bundled conductor E_S in comparison with the maximal field intensity of single conductor E_V

Bundled conductors

- It is assumed, that the total cross section of both arrangements is the same

$$n\pi R_S^2 = \pi R_V^2$$
$$\Rightarrow R_V = R_S\sqrt{n}$$

- The ratio between E_S and E_V is

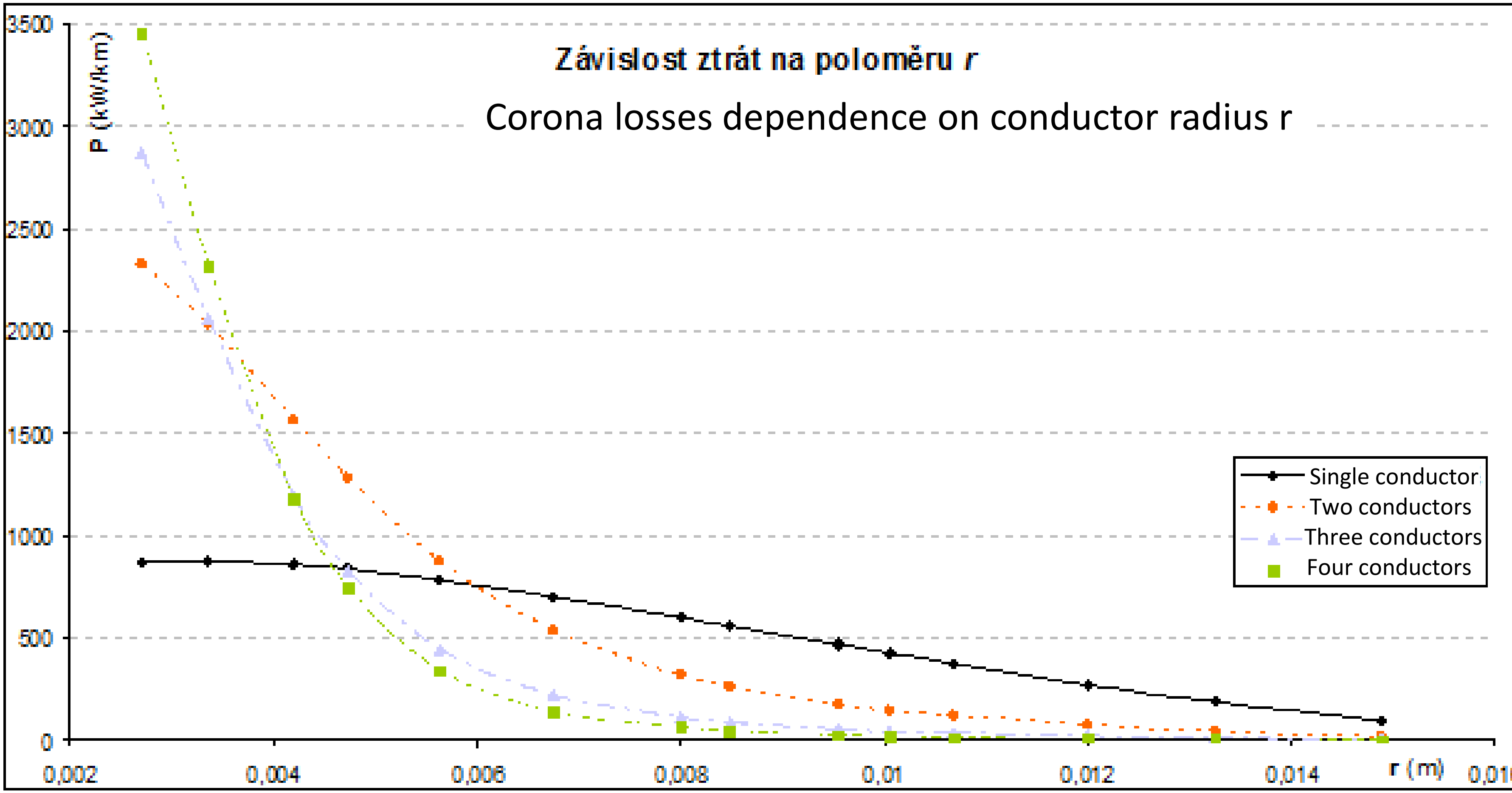
$$\frac{E_S}{E_V} = \frac{R_S}{2\sqrt{n}} \sum_{i=1}^{n} \frac{r - \rho\cos\left(\frac{2\pi}{n}(i-1)\right)}{r^2 + \rho^2 - 2\,r\rho cos\left(\frac{2\pi}{n}(i-1)\right)}$$

Bundled conductors

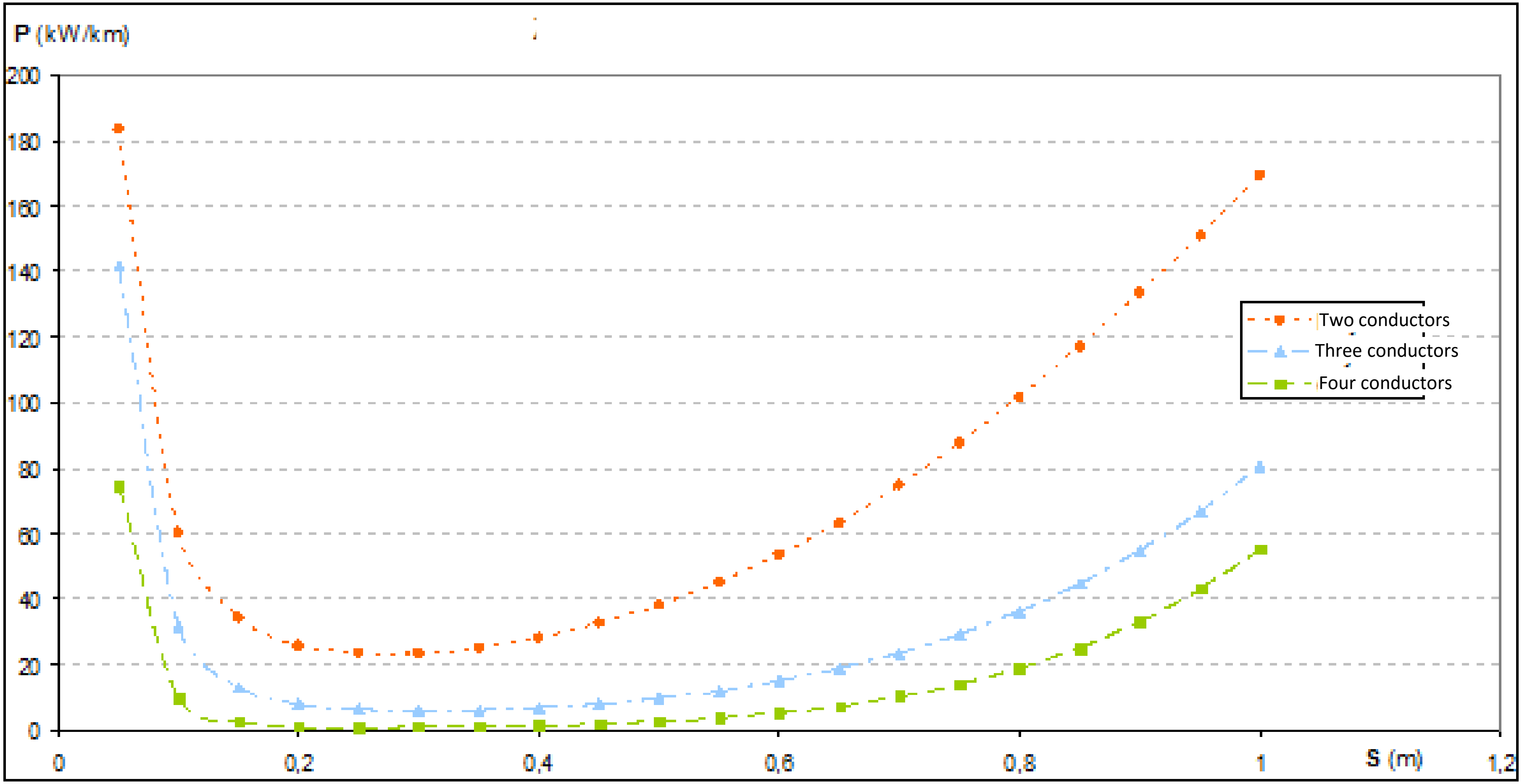
- The formula can be simplified, if the condition that r ≅ ρ (ρ >>R_S) is taken into account

$$\frac{E_S}{E_V} = \frac{1 + (n-1)R_S}{2\rho\sqrt{n}}$$

Example of corona losses dependence on conductor radius r

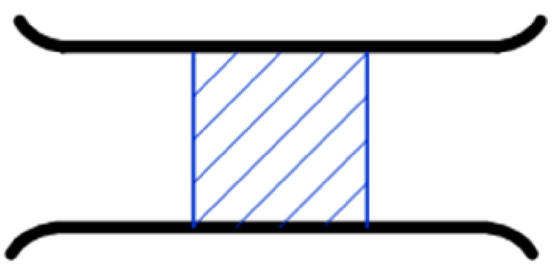


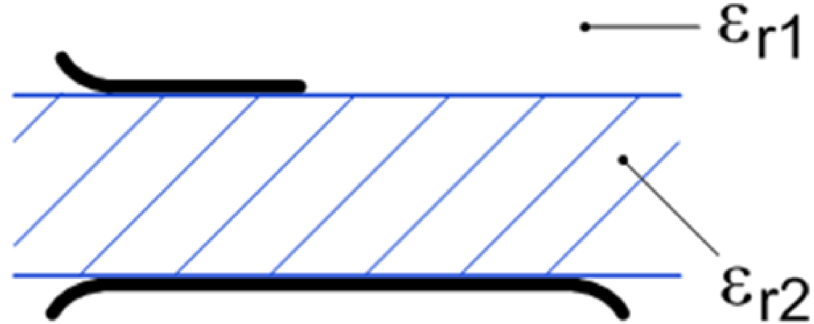
Influence of conductor's distance S to corona losses



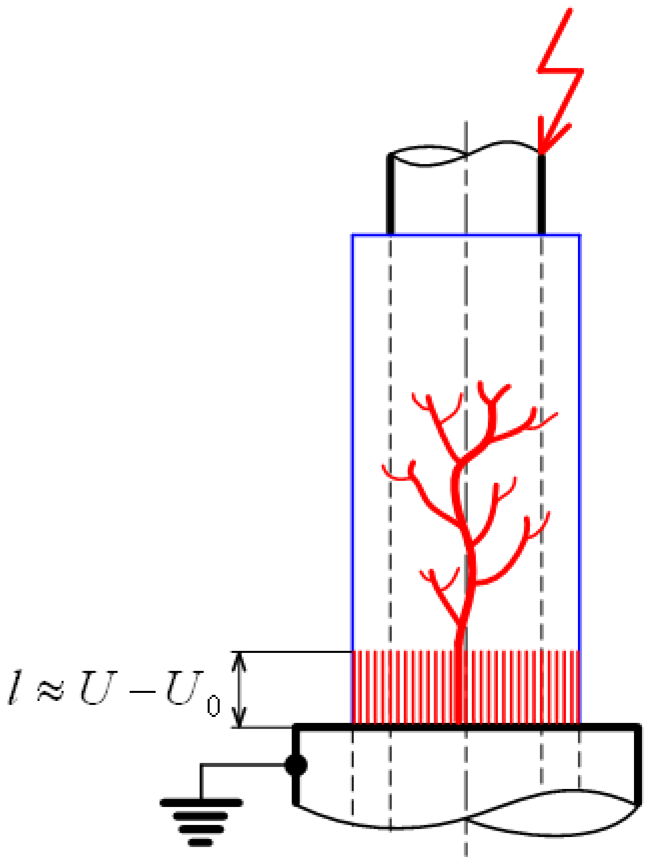
Surface discharges

- The longitudinal component of electric field intensity is created when the electric field lines enter obliquely the boundary of two dielectrics (air-insulator)
- The surface discharges arise when the longitudinal component cross the electric strength of the boundary air-insulator





Development of surface discharges along the bushing



$$U_0 = \frac{k}{c^{0,45}} \quad (kV;\, pF/mm^2)$$

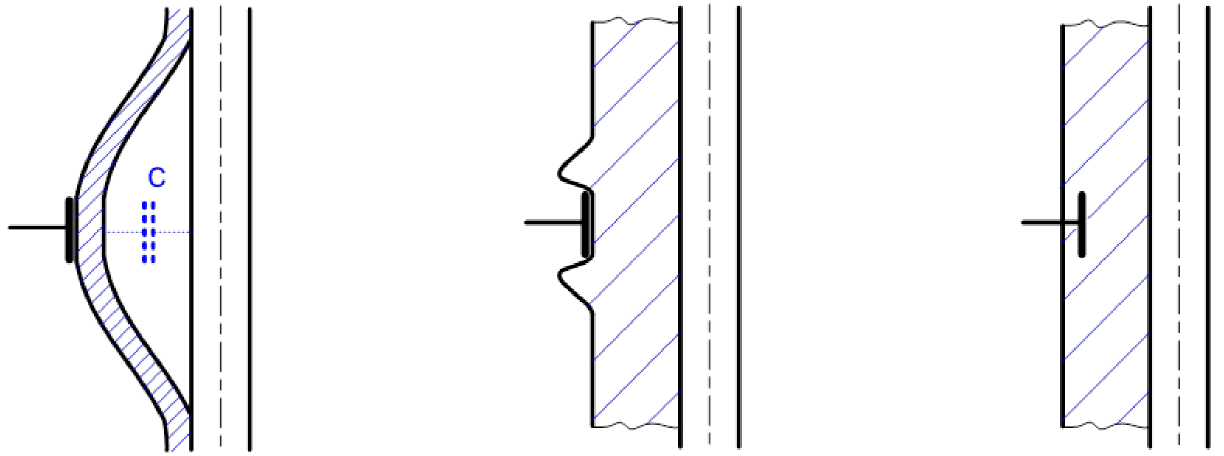
$$k \cong 0,34$$

$$U_S = \frac{k_S}{c^{0,45}} \quad (kV;\, pF/mm^2)$$

$$k_S \cong 10\, k$$

Mitigation of surface discharges

- Design optimalization



- Control of electric field distribution
  - Condenser bushing (capacitance-graded)
  - Resistive paintings

Bushings

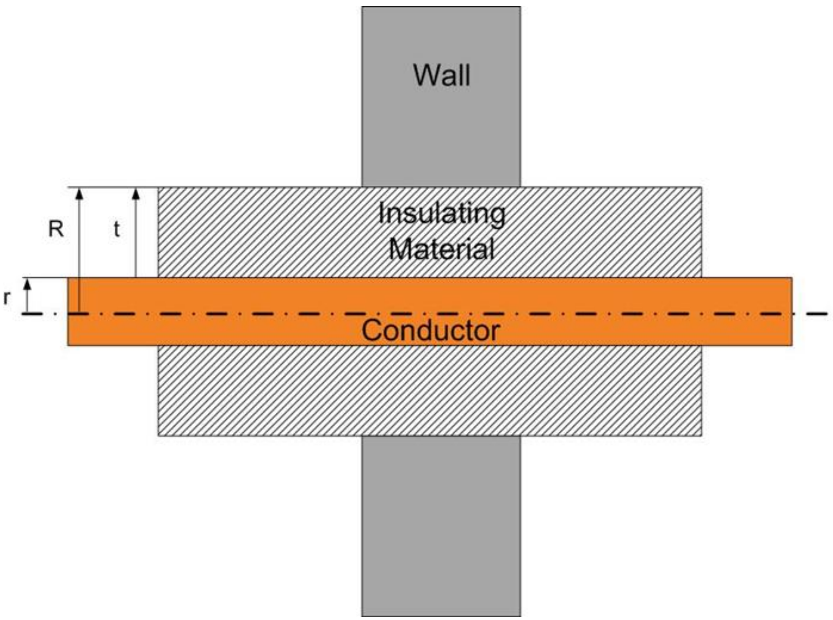
Intenzita el. pole u válcového uspořádání

$$E = \frac{U}{x\,Ln\left(\frac{R}{r}\right)}$$

Maximální hodnota bude na povrchu vodiče:

$$E_{max} = \frac{U}{r\,Ln\left(\frac{r+t}{r}\right)}$$

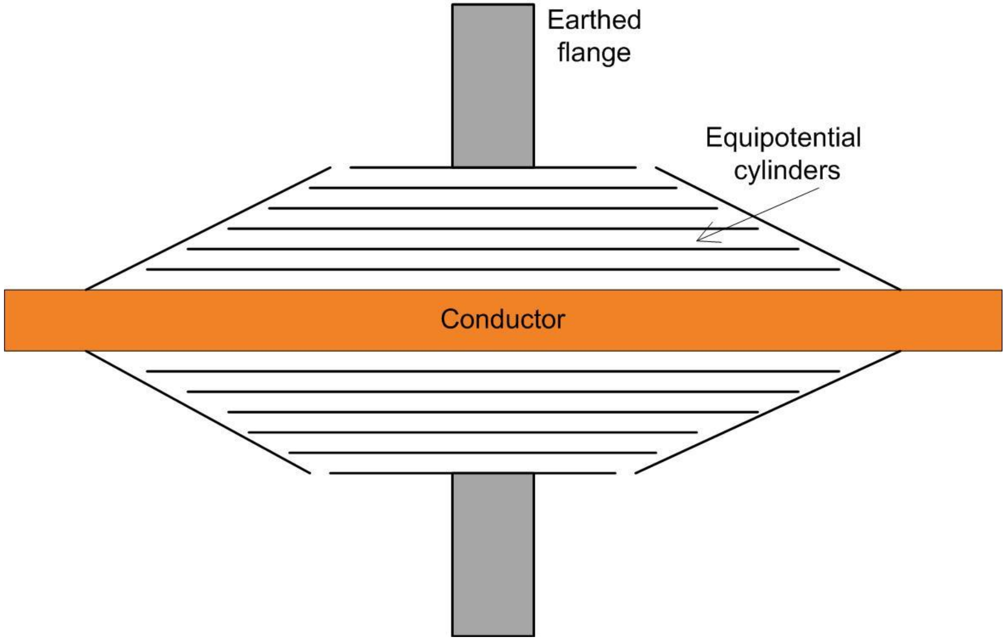
$$\Rightarrow t = \mathrm{r}\left[e^{\frac{U}{rE_{max}}} - 1\right]$$



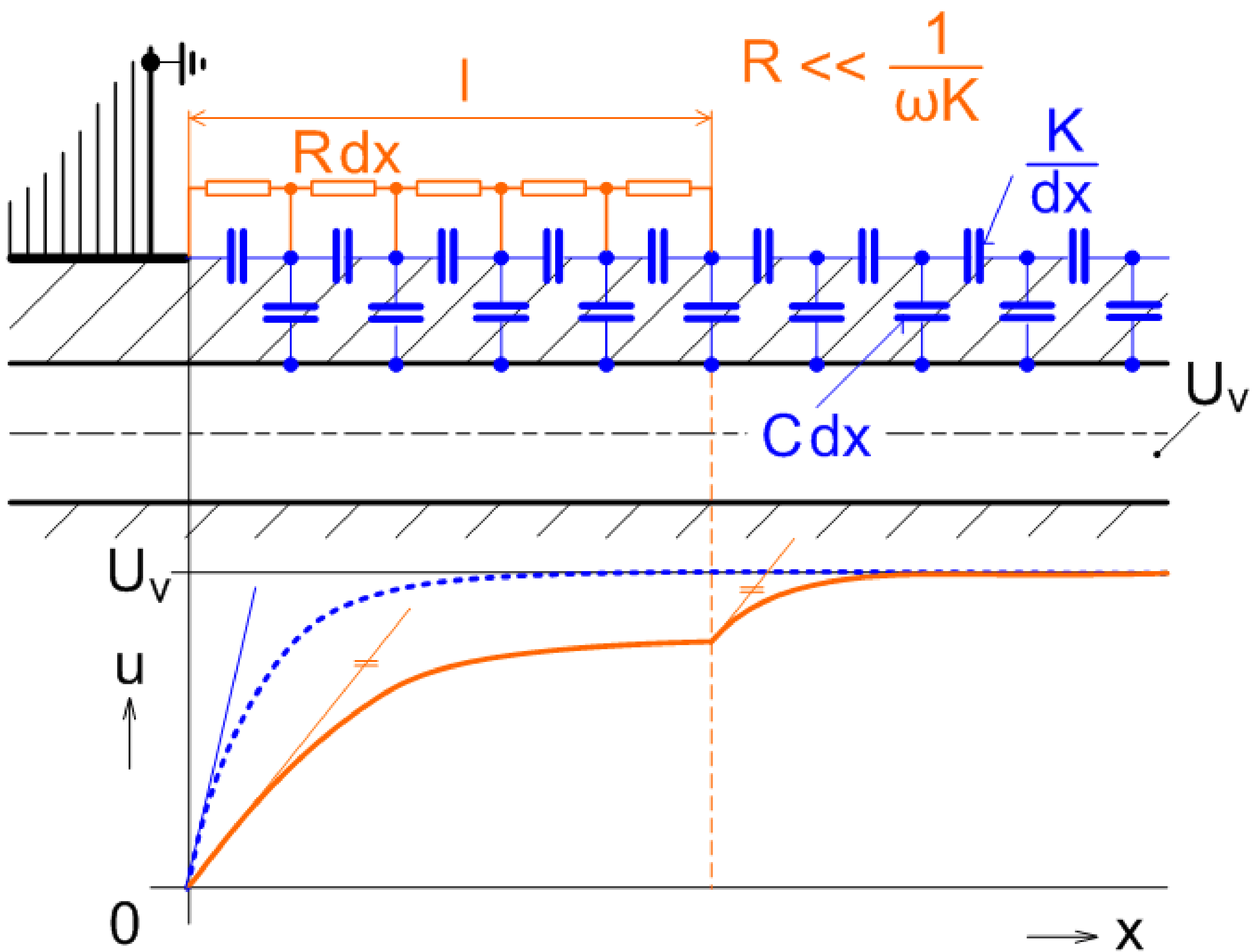
Condenser bushings

– Uniformly distributed voltage

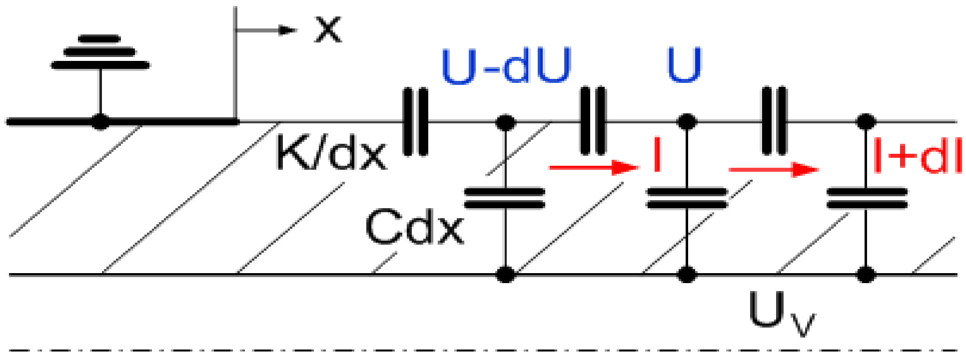
$$E_{max} = \frac{U}{t} \Rightarrow t = \frac{U}{E_{max}}$$



Resistive surface paintings



Equivalent circuit



$K \dots (F \cdot m)$
$C \dots (F \cdot m^{-1})$

Equivalent electric circut equations:

$$I - (I + dI) = j\omega C dx (U - U_V)$$

$$(U - dU) - U = I \frac{dx}{j\omega K}$$

After adjustement:

$$\frac{dI}{dx} = -j\omega C (U - U_V) \quad a \quad \frac{dU}{dx} = \frac{jI}{\omega K}$$

Solution of circuit equations

The derivative of second equation with respect to x:

$$\frac{d^2U}{dx^2} = \frac{dI}{dx}\frac{j}{\omega K} \Longrightarrow \frac{dI}{dx} = \frac{\omega K}{j}\frac{d^2U}{dx^2}$$

Substitution to the first equation:

$$j\omega K\frac{d^2U}{dx^2} = j\omega C(U - U_V)$$

and after the adjustement:

$$\frac{d^2U}{dx^2} = \frac{C}{K}(U - U_V)$$

Solution of circuit equations

Assuming $U(\infty)=U_V$ the general solution has a form:

$$U = Ae^{x\sqrt{\frac{C}{K}}} + Be^{-x\sqrt{\frac{C}{K}}} + U_V$$

when the constant A must be equal to 0. Constant B can be stated from the second assumption U(0)=0, then $B=-U_V$. The final solution is:

$$U = U_V\left[1 - e^{-x\sqrt{\frac{C}{K}}}\right]$$

Surface Electric Field Intensity

Electric field intensity can calculated as:

$$\frac{dU}{dx} = U_V \sqrt{\frac{C}{K}} e^{-x\sqrt{\frac{C}{K}}}$$

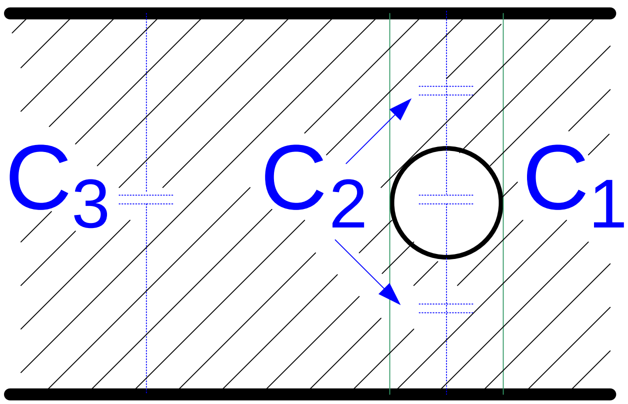
The maximal intensity is at the origin i.e. x=0:

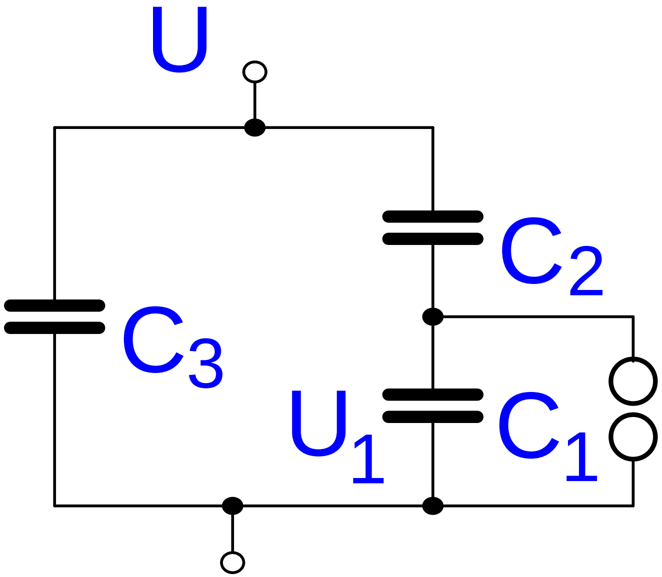
$$E_0 = U_V \sqrt{\frac{C}{K}}$$

Partial discharges

- Partial discharge is the local electric discharge which partialy bridges insulation between electrodes when the rest of insulation system withstand the operating or testing voltage
- Partial discharges are generaly the result of local electric stress concentration both inside the insulation and on its surface
- The corona discharge is a form of partial discharge in gases at the electrode which is spaced from the solid or liquid insulator

Equivalent circuit





The voltage across the cavity U_1 can be expressed as:

$$U_1 = \frac{C_2}{C_1 + C_2} U$$

Apparent charge

- For the simplicity, the zero extinguishing voltage is assumed
- During the discharge the voltage drops from the value U to U_V

From the charge equivalency in the equivalent circuit:

$$\left(C_3 + \frac{C_1 C_2}{C_1 + C_2}\right) U = (C_3 + C_2) U_V$$

Apparent charge

The voltage U_V can be expressed as:

$$U_V = \frac{C_1 C_2 + C_1 C_3 + C_2 C_3}{(C_1 + C_2)(C_3 + C_2)} U$$

- Denote U_{1z} as ignition voltage and assume that $U_{1z}=U_1$

Then, the final formula for the voltage U_v is:

$$U_V = \frac{C_1 C_2 + C_1 C_3 + C_2 C_3}{C_2 (C_3 + C_2)} U_{1z}$$

Apparent charge

- Discharge inside the cavity causes the voltage drop U-U_v

$$\Delta U = U - U_V$$
$$= \frac{C_1(C_3 + C_2) + C_2(C_3 + C_2) - C_1C_2 - C_1C_3 - C_2C_3}{C_2(C_3 + C_2)} U_{1z}$$
$$= \frac{C_2}{C_2 + C_3} U_{1z}$$

Apparent discharge

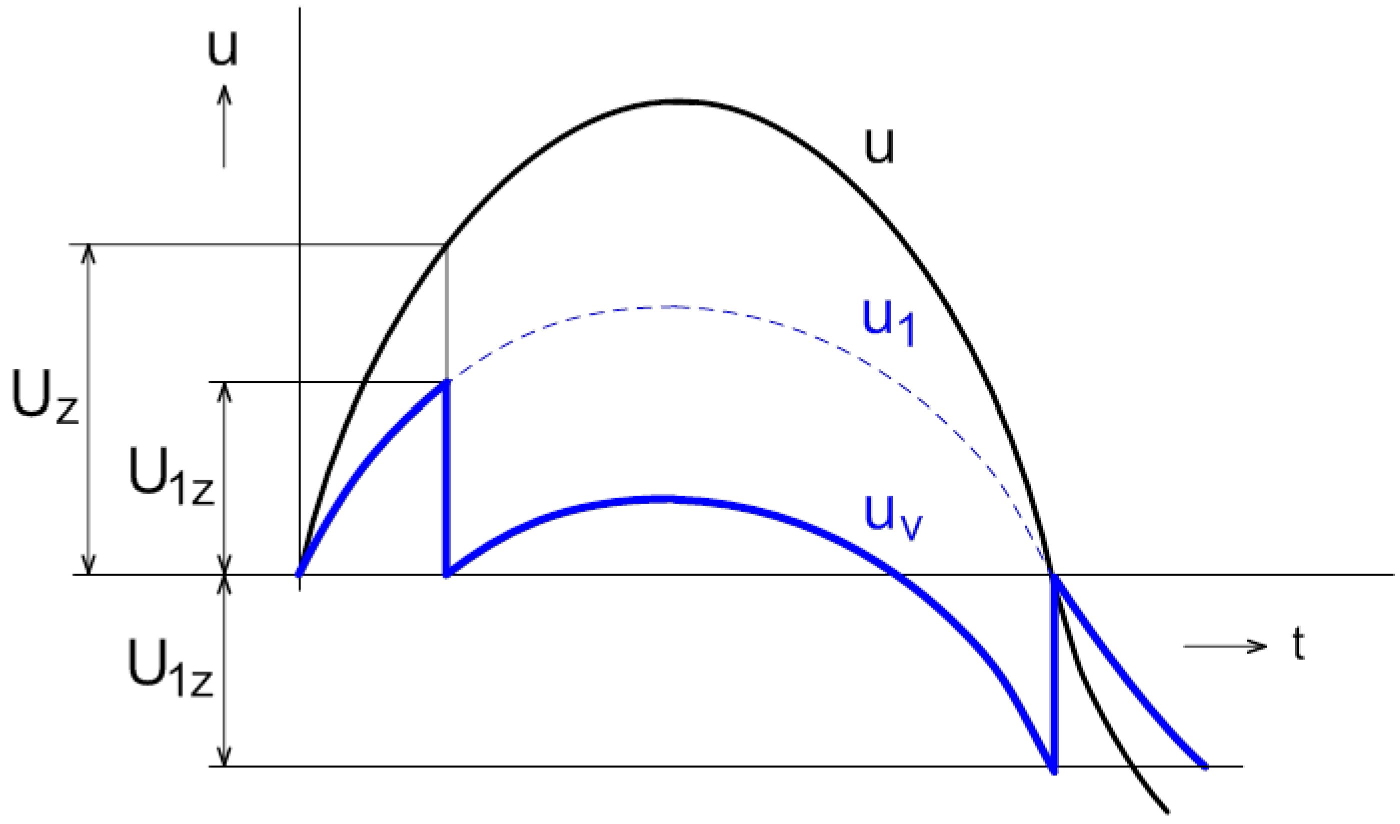
- Apparent discharge Δq can be then expressed by total capacity and voltage drop as

$$\Delta q = \left(C_3 + \frac{C_1 C_2}{C_1 + C_2} \right) \Delta U$$
$$= \frac{C_2 C_3 (C_1 + C_2) + C_1 C_2^2}{(C_1 + C_2)(C_2 + C_3)} U_{1z}$$

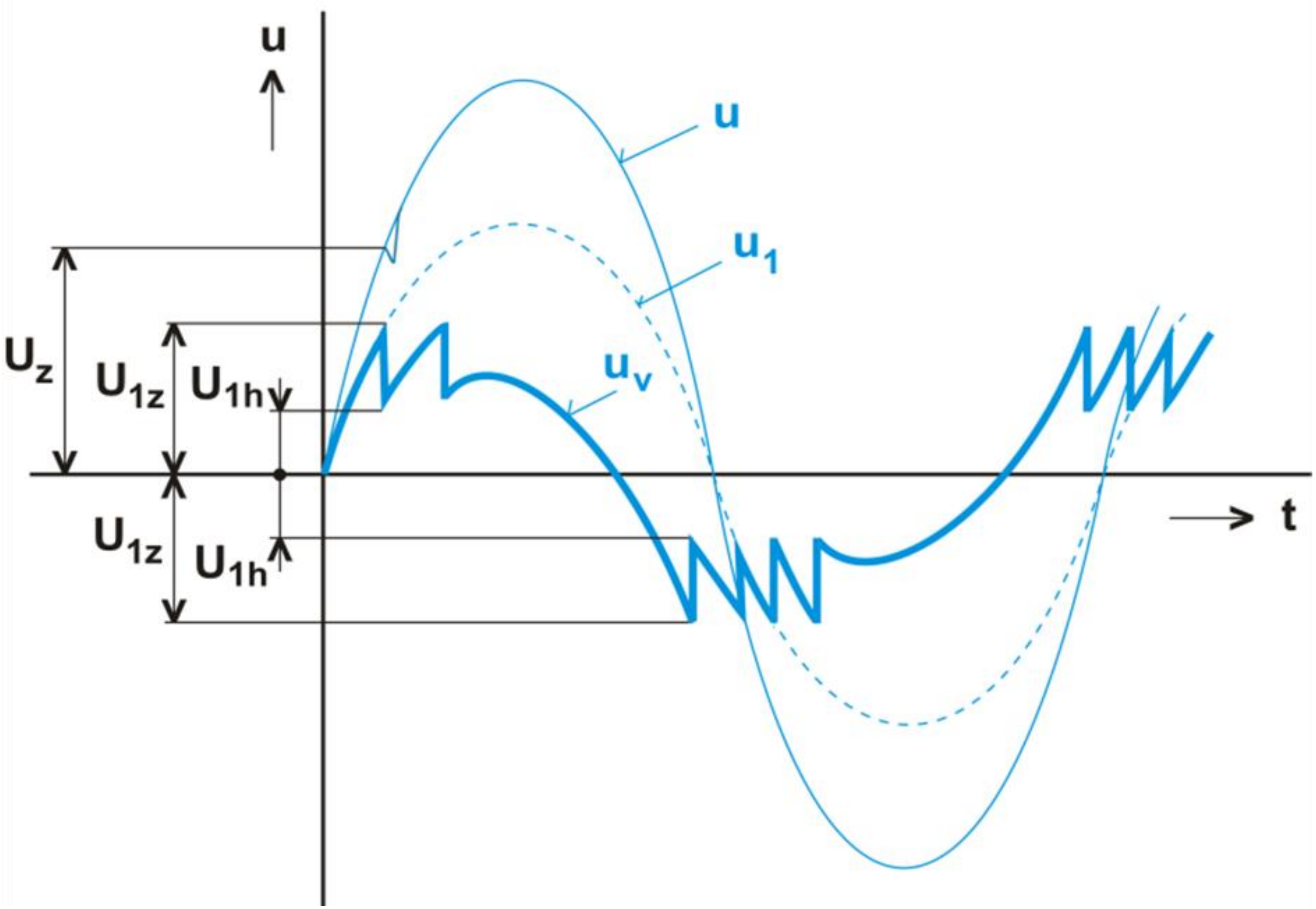
- Assuming (C_1 a C_2)<<C_3

$$\Delta q \doteq C_3 \Delta U \,; \Delta U \doteq \frac{C_2}{C_3} U_{1z} \implies \Delta q \doteq C_2 U_{1z}$$

Formation of partial discharges



Formaton of partial discharges during one period – non-zero extinguishing voltage



Influence of partial discharges to electric strength

- Electric effects
  - Presence of arc in a cavity and high concentration of electric field at the end of conductive path can cause intrinsic breakdown
- Erosion effects
  - Erosion of cavity walls, gradually transitioning in breakdown
- Chemical effects
  - Long-term decomposition of insulator by products of discharge
- Thermal effects
  - Thermal nonstability and voltage drop by thermal breakdown