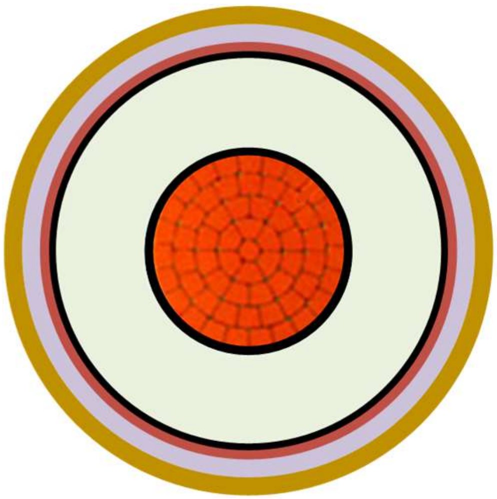
EEN-206: Power Transmission and Distribution

Lecture - 16

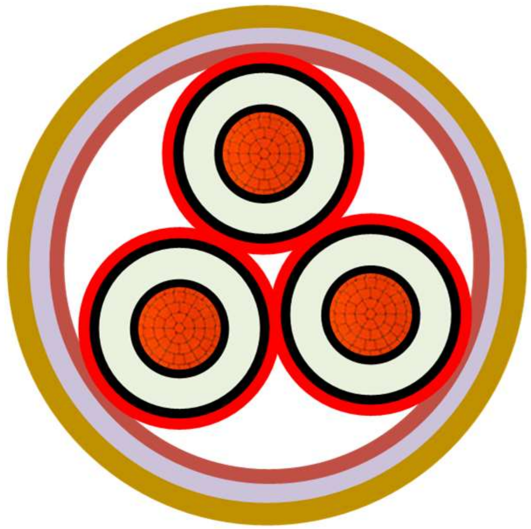
Chapter 3: Underground Cables

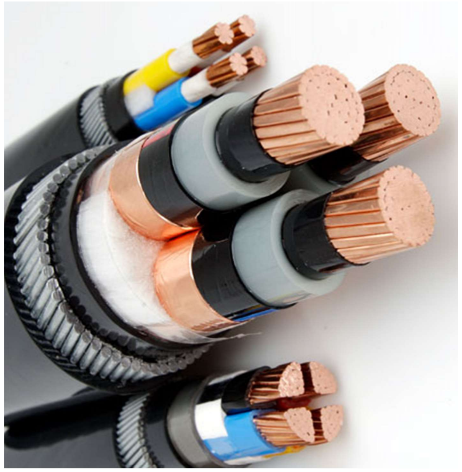
- **Parameters of the Cable**
- **Other important topics**

Single Core and Three Core Cables



Single Core (conductor) Cable

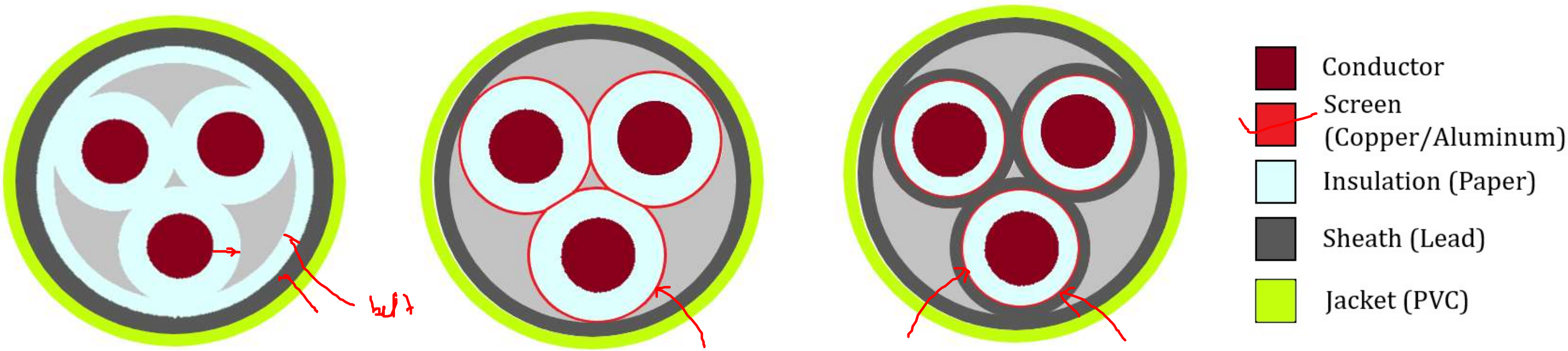




Three Core (conductor) Cable (Below 66 kV)

Gonen T., *Electric Power Transmission System Engineering Analysis and Design*, CRC Pres, 2010.

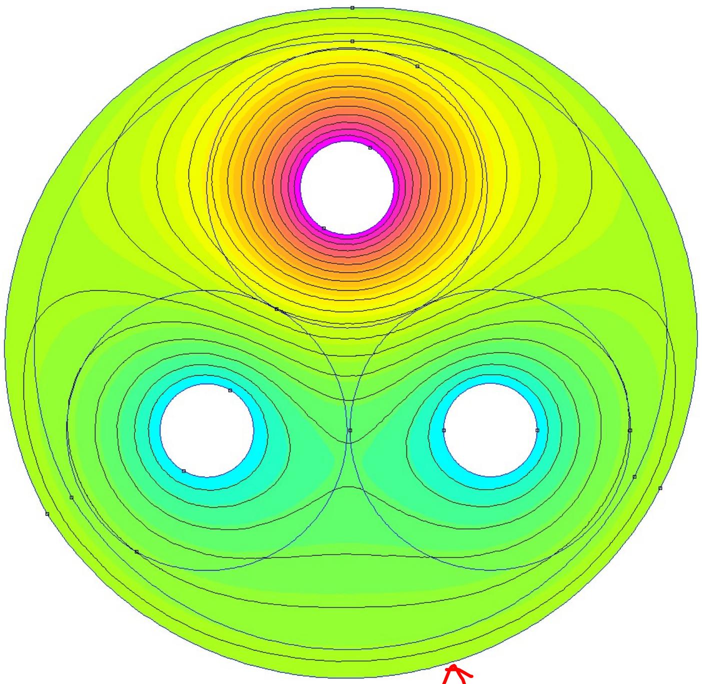
Belted and Screened or shielded Cable



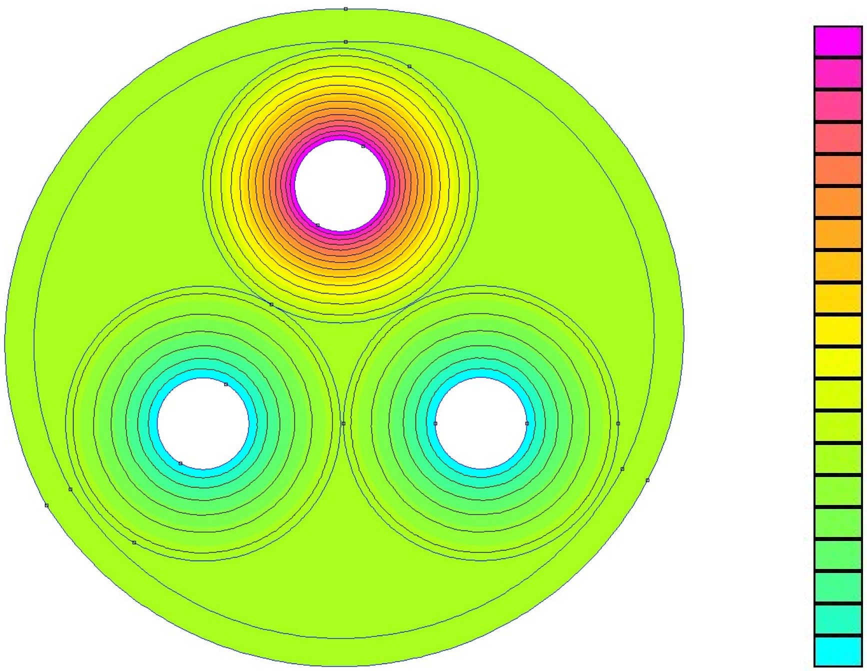
Belted *H-Type Screened* *S. L. Type Screened*

- Belted cables are used up to 11 kV.
- There are two types of screened cables used up to 33 kV
  - H-Type (Hochstadter)
  - S.L. type (Separate lead).

Electric Field 3-Phase Cables



Belted

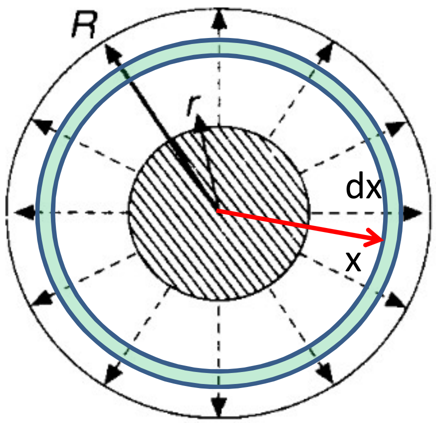


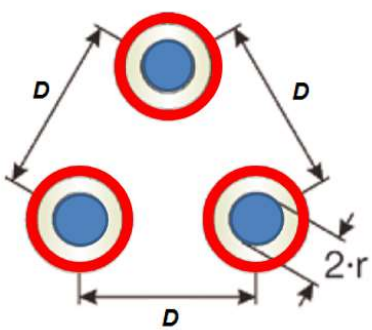
H-Type Screened and S. L. Type Cables

Electrical Parameters of Cables

- Insulation resistance
- Cable inductance
- Cable capacitance
- Electrical stress inside insulation
  - Grading of cable
    - Capacitance grading
    - Inter-sheath grading
- Dielectric losses and tan delta (loss tangent)
- Breakdowns in cable insulations (Solid Insulation)

Insulation Resistance





- **Insulation resistance per unit length**

$$R_s = \frac{\rho}{2\pi} \ln \frac{R}{r} \quad \Omega.\text{m}$$

- **Inductance per unit length**

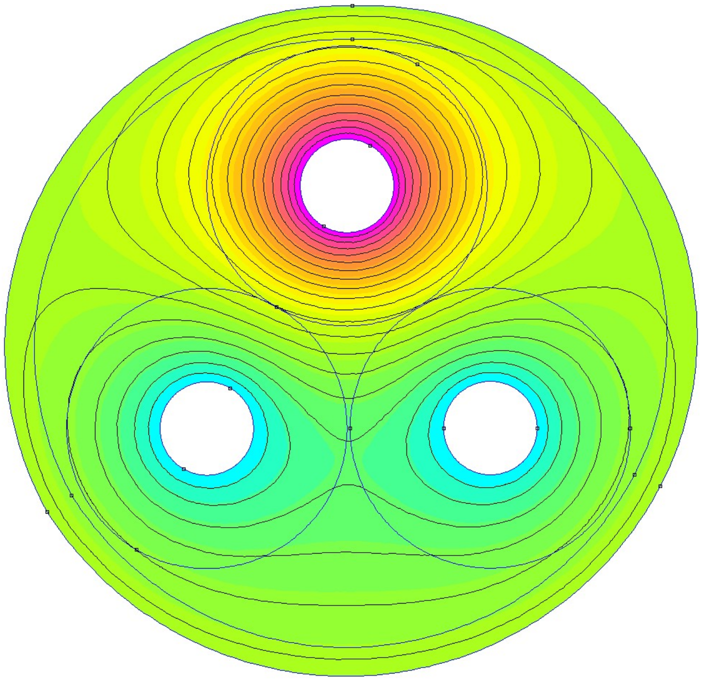
$$\boxed{L = 2\times 10^{-7} \ \ln \frac{D}{r'} \quad \text{H/m}}$$

D = separation distance between phase conductor
r' =0.7788*r* (solid conductor use GMR for stranded conductor)
r = radius of the conductor

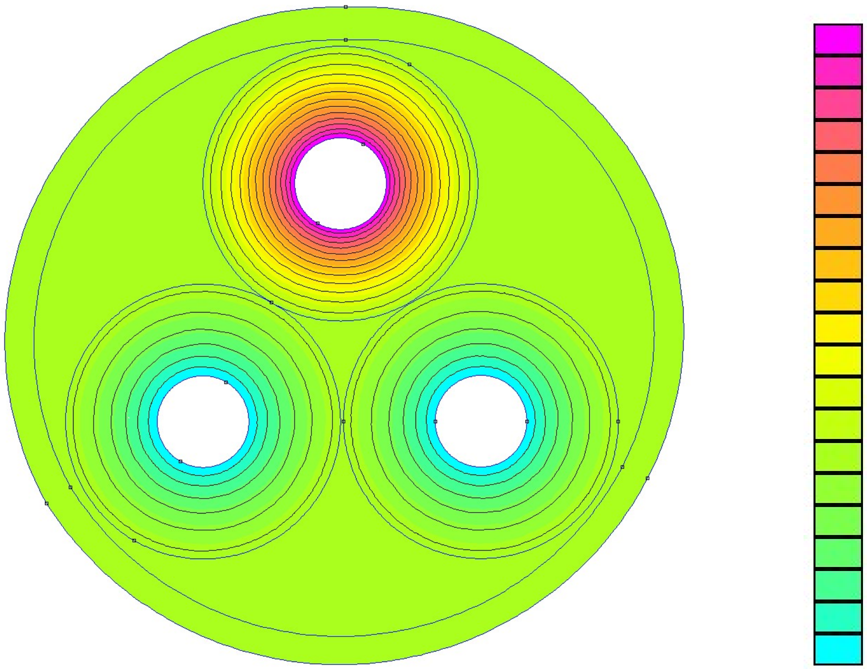
- **Capacitance of cable per unit length**

$$\boxed{C = \frac{q}{V} = \frac{2\pi\varepsilon}{\ln \dfrac{R}{r}} \quad \text{F/m}}$$

Electric Field Three-Core Cables



Belted Cable



H-Type Screened and S. L. Type Cables

Capacitance of Three-Core Belted Cable

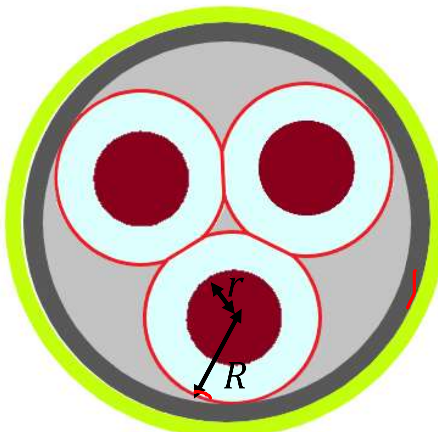
Belted Cable

$$\boxed{C_0 = \frac{0.0298\varepsilon_r}{\log_{10}\left(1+\frac{T+t}{d}\left(3.84-1.70\frac{t}{T}+0.52\frac{t^2}{T^2}\right)\right)} \quad \mu\text{F/km}}$$

- ε_r = the relative permittivity of the insulation,
- t = thickness of belt insulation,
- d = diameter of the conductor and
- T = conductor insulation thickness.

Legend:

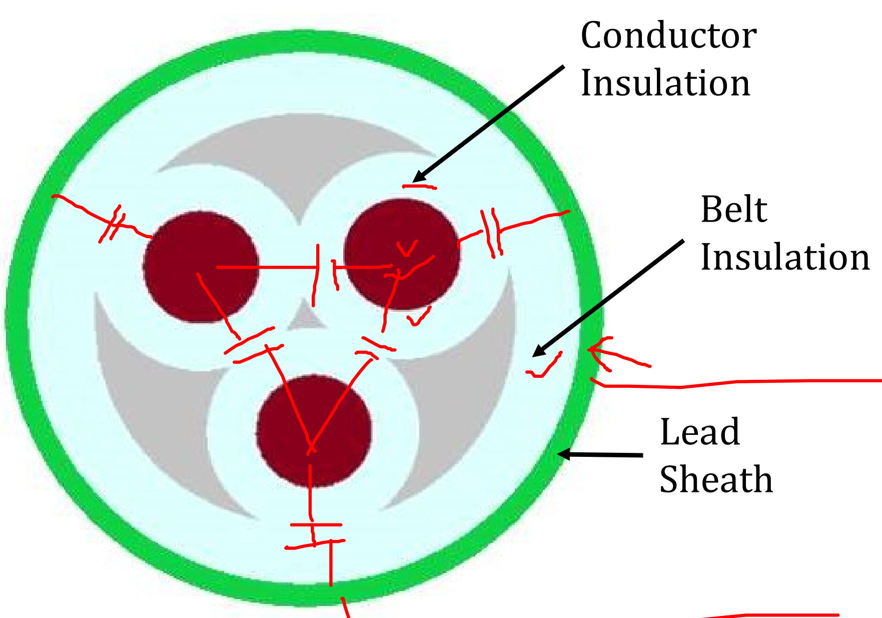
- Conductor
- Screen (Copper/Aluminum)
- Insulation (Paper)
- Sheath (Lead)
- Jacket (PVC)

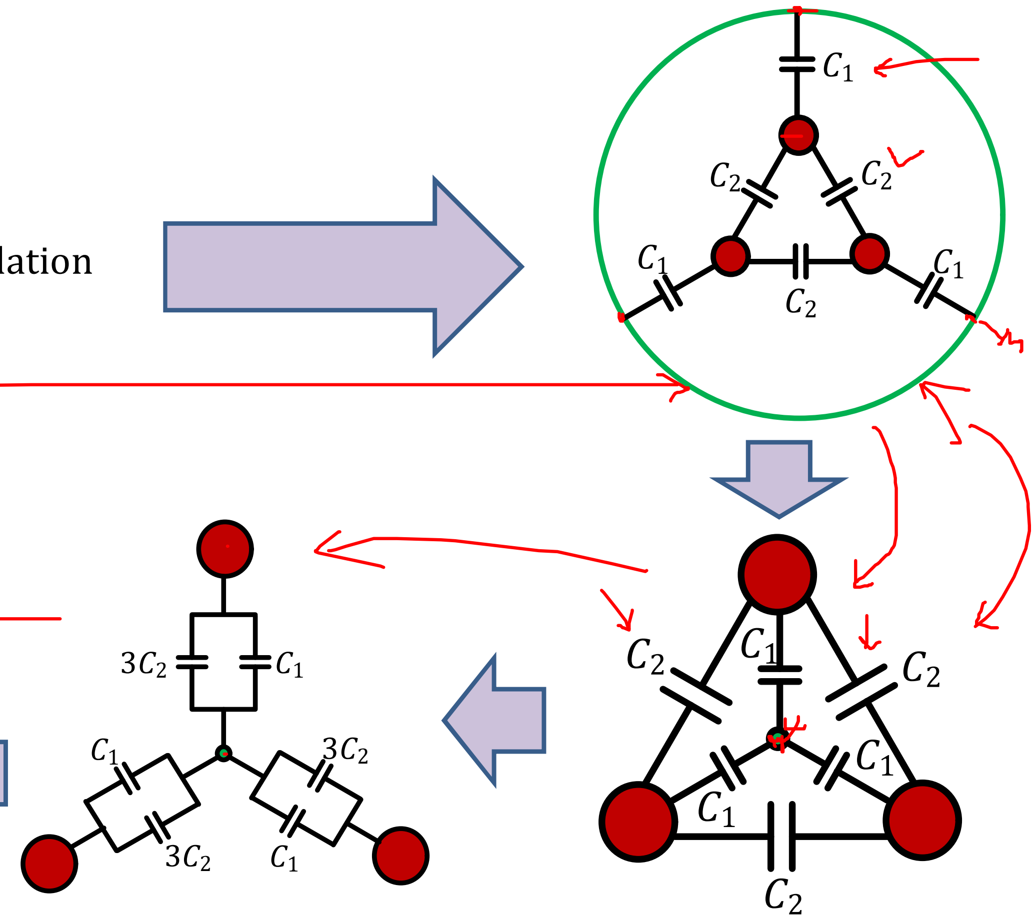


H-Type Screened and S. L. Type Cables

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(\frac{R}{r}\right)} \text{ F/m}$$

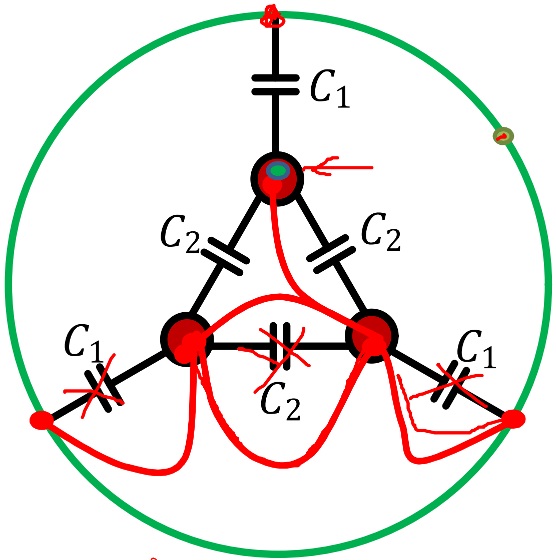
Capacitance of Three-Core Belted Cable





$$\boxed{C_0 = C_1 + 3C_2}$$

How to find C_1 and C_2



$C_0 + \frac{3C_y}{2} + \frac{C_x}{6}$

Take following measurements:

1. All the three conductors joined together and measure the capacitance (C_x) between sheath and conductors.

$$C_x = 3C_1 \Rightarrow C_1 = C_x/3$$

1. Connect two conductors and sheath together and measure the capacitance (C_y) between sheath and remaining conductors

$$C_y = 2C_2 + C_1 \Rightarrow C_2 = \frac{C_y}{2} - \frac{C_1}{2} = \frac{C_y}{2} - \frac{C_x}{6}$$

Therefore $\boxed{C_0 = C_1 + 3C_2 = \frac{C_x}{3} + 3\left(\frac{C_y}{2} - \frac{C_x}{6}\right) = \frac{3C_y}{2} - \frac{C_x}{6}}$

Electric Stress in The Cable

$$E_x = \frac{q}{2\pi\varepsilon x} \Rightarrow V = \frac{q}{2\pi\varepsilon}\ln\frac{R}{r}$$

$$\frac{q}{2\pi\varepsilon} = \frac{V}{\ln\frac{R}{r}}$$

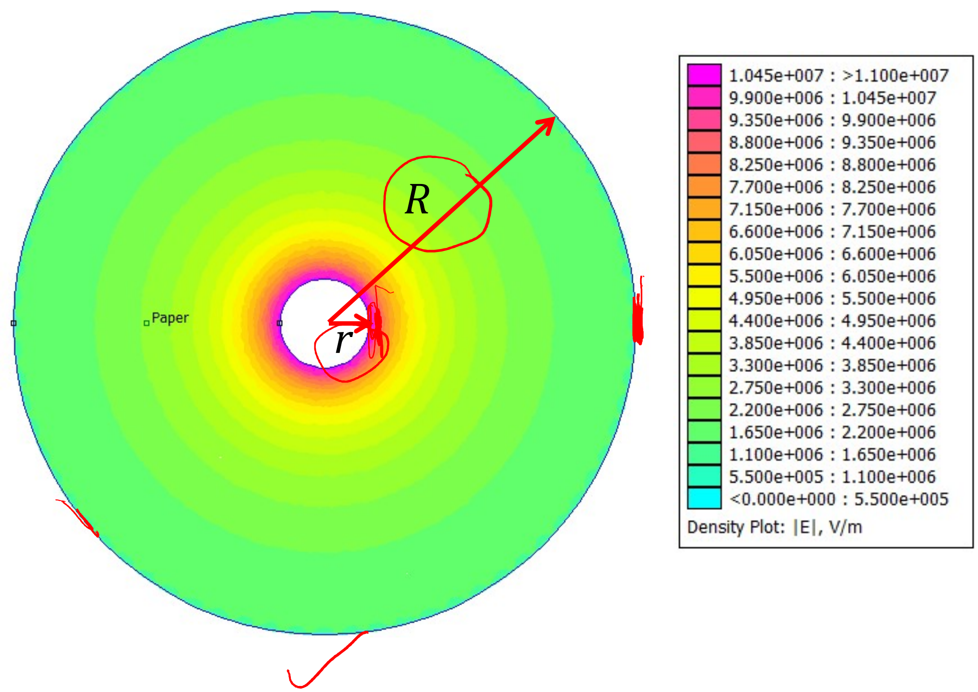
$$\boxed{E_x = \frac{V}{x\ln\frac{R}{r}}}$$

- Maximum stress occurs at the surface of conductor

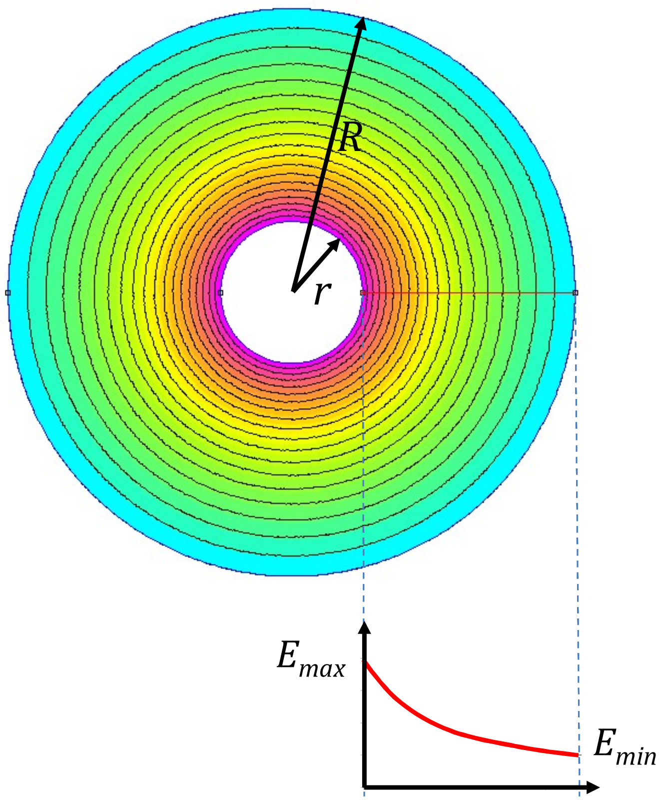
$$E_{\max} = \frac{V}{r\,\ln\frac{R}{r}}$$

- Minimum stress occurs at the sheath surface

$$E_{\min} = \frac{V}{R\,\ln\frac{R}{r}}$$



Electric Stress in The Cable



$$E_{\max} = \frac{V}{r \ln \frac{R}{r}}$$

- Minimum E_{max} means maximization of $r \ln \frac{R}{r}$

$$\frac{d}{dr}\left(r \ \ln\left(\frac{R}{r}\right)\right) = 0$$

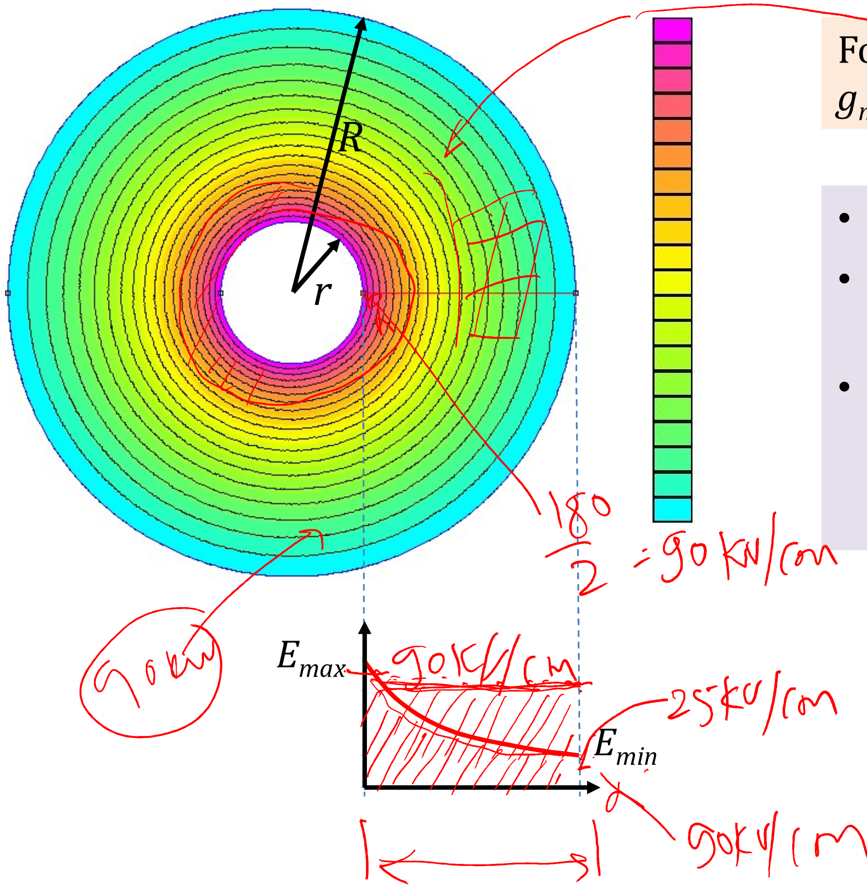
$$r \ \frac{r}{R}\left(-\frac{R}{r^2}\right) + \ln\frac{R}{r} = 0$$

$$-1 \ + \ \ln\left(\frac{R}{r}\right) = 0$$

$$\ln\left(\frac{R}{r}\right) = 1 \quad \text{OR} \quad \boxed{\frac{R}{r} = e}$$

$$E_{\max} = \frac{V}{r}$$

Grading of Cables

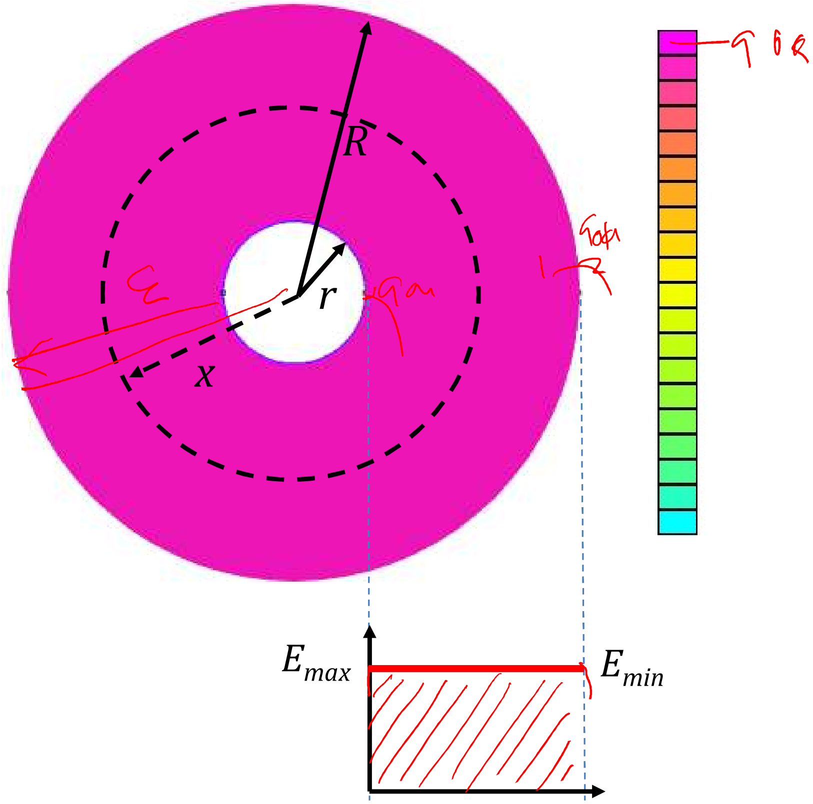


For XLPE with safety factor 2 180 kV/cm

g_{max} =180/2 = 90 kV/cm

- Thus insulation material is not properly utilized.
- Grading is used to decrease difference between E_{max} and E_{min}.
- Grading can be broadly classified into two categories.
  - Capacitance Grading
  - Intersheath Grading

Capacitance Grading (Ideal)



g_{max} = 90 kV/cm
g_{min} = 90 kV/cm

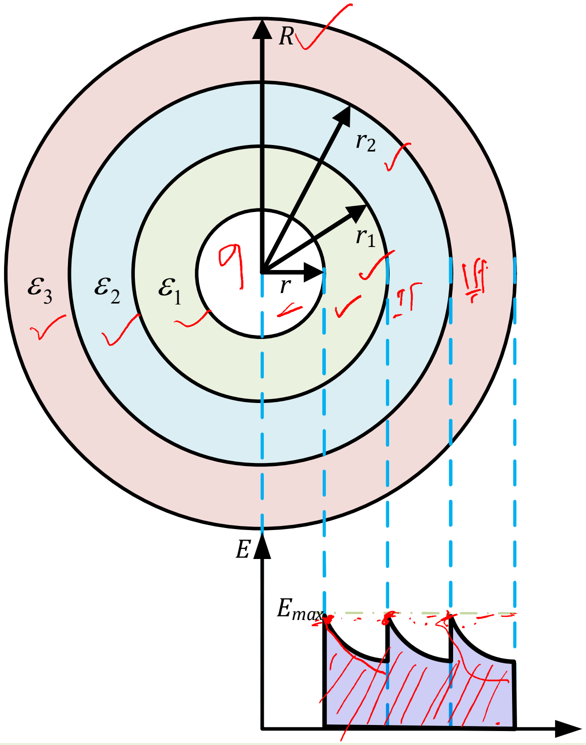
$$E(x) = \frac{q}{2\pi\varepsilon x} = k$$

Therefore the permittivity is

$$\varepsilon = \frac{k_1}{x}$$

- This is ideal condition for stress in a cable.
- However, this cannot be realized in practice since it requires infinite number of dielectric materials with varying permittivity
- In practice, this can be realized by two or three layers of the dielectric materials.

Capacitance Grading (With Same Maximum Stress)



- If the materials are subjected to same maximum stress at the r , r_1, *and* r_2

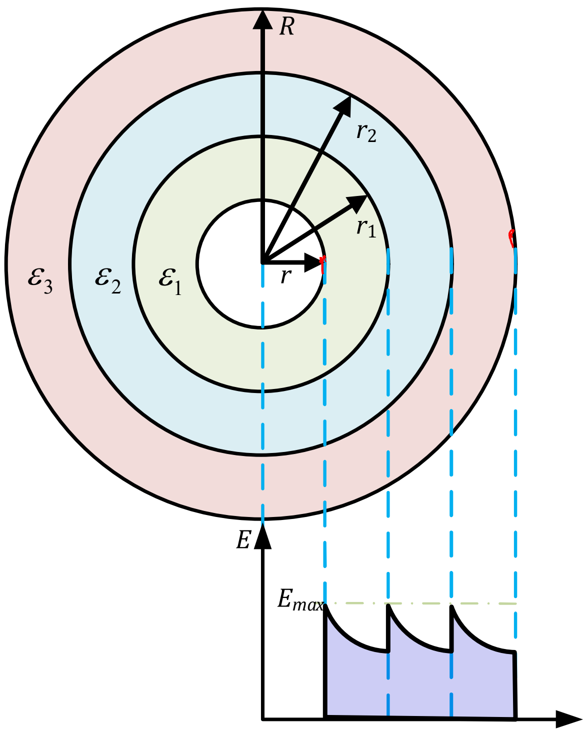
$$E_{\max 1} = E_{\max 2} = E_{\max 3}$$

Layer 1 (ε_1) $\quad r < x < r_1$	
$E_1(x) = \dfrac{q}{2\pi\varepsilon_1 x}$	$\boxed{E_{\max 1} = \dfrac{q}{2\pi\varepsilon_1 r}}$ 1

Layer 2 (ε_2) $\quad r_1 < x < r_2$	
$E_2(x) = \dfrac{q}{2\pi\varepsilon_2 x}$	$\boxed{E_{\max 2} = \dfrac{q}{2\pi\varepsilon_2 r_1}}$ 2

Layer 3 (ε_3) $\quad r_2 < x < R$	
$E_3(x) = \dfrac{q}{2\pi\varepsilon_3 x}$	$\boxed{E_{\max 3} = \dfrac{q}{2\pi\varepsilon_3 r_2}}$ 3

Capacitance Grading (With Same Maximum Stress)



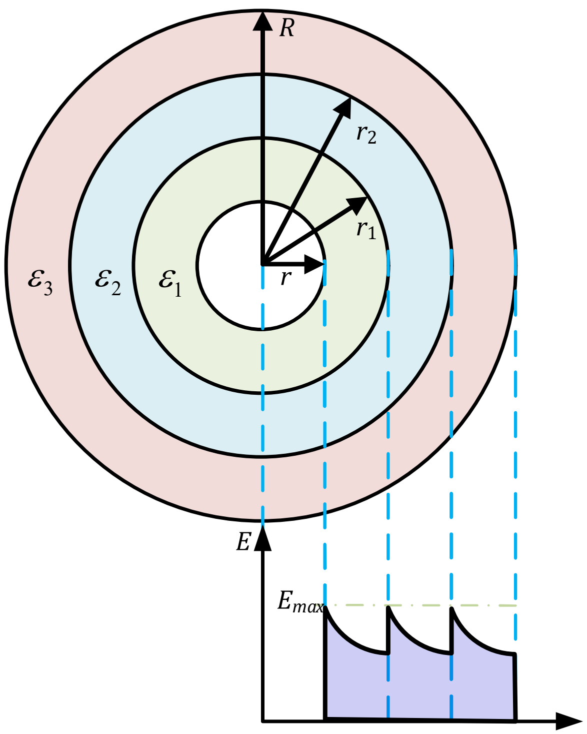
$$E_{\max} = \frac{\cancel{q}}{\cancel{2\pi}\varepsilon_1 r} = \frac{\cancel{q}}{\cancel{2\pi}\varepsilon_2 r_1} = \frac{\cancel{q}}{\cancel{2\pi}\varepsilon_3 r_2}$$

$$\varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 r_2$$

- Since $r < r_1 < r_2$ $\Rightarrow$ $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$

- Therefore, same maximum stress, material having highest permittivity needs to be kept near to the surface of conductor.

Capacitance Grading (With Same Maximum Stress)



Layer 1 (ε_1) $r < x < r_1$	**Layer 2 (ε_2)** $r_1 < x < r_2$	**Layer 3 (ε_3)** $r_2 < x < R$
$E_1(x) = \dfrac{q}{2\pi\varepsilon_1 x}$	$E_2(x) = \dfrac{q}{2\pi\varepsilon_2 x}$	$E_3(x) = \dfrac{q}{2\pi\varepsilon_3 x}$
$E_{\max} = \dfrac{q}{2\pi\varepsilon_1 r}$	$E_{\max} = \dfrac{q}{2\pi\varepsilon_2 r_1}$	$E_{\max} = \dfrac{q}{2\pi\varepsilon_3 r_2}$

$$V = \int_r^{r_1} E_1\,dx + \int_{r_1}^{r_2} E_2\,dx + \int_{r_2}^{R} E_3\,dx$$

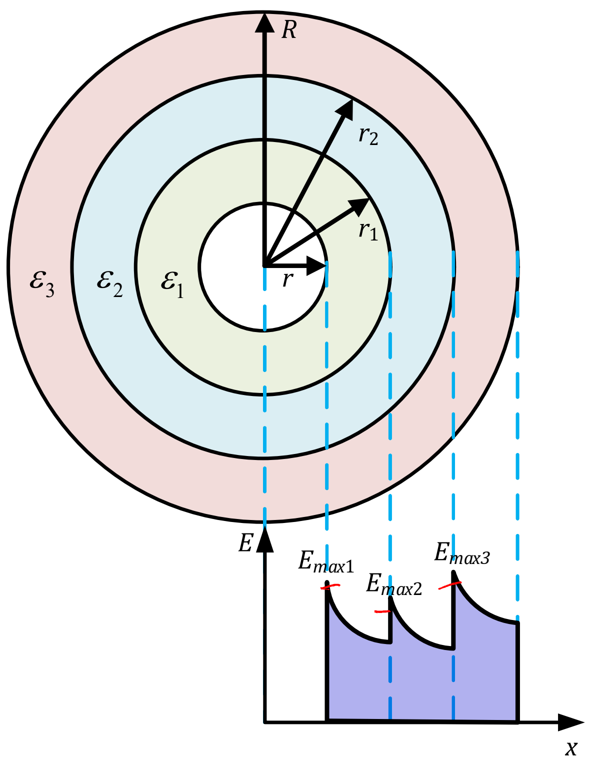
$$= \frac{q}{2\pi\varepsilon_1}\ln\frac{r_1}{r} + \frac{q}{2\pi\varepsilon_2}\ln\frac{r_2}{r_1} + \frac{q}{2\pi\varepsilon_1}\ln\frac{R}{r_2}$$

$$= \frac{q}{2\pi\varepsilon_1}\frac{r}{r}\ln\frac{r_1}{r} + \frac{q}{2\pi\varepsilon_2}\frac{r_1}{r_1}\ln\frac{r_2}{r_1} + \frac{q}{2\pi\varepsilon_1}\frac{r_2}{r_2}\ln\frac{R}{r_2}$$

$$= E_{\max}\, r \ln\frac{r_1}{r} + E_{\max}\, r_1 \ln\frac{r_2}{r_1} + E_{\max}\, r_2 \ln\frac{R}{r_2}$$

$$\boxed{V = E_{\max}\left(r \ln\frac{r_1}{r} + r_1 \ln\frac{r_2}{r_1} + r_2 \ln\frac{R}{r_2}\right)}$$

Capacitance Grading (With Different Maximum Stress)



- If the materials are subjected to different maximum stress at the r , r_1, *and* r_2

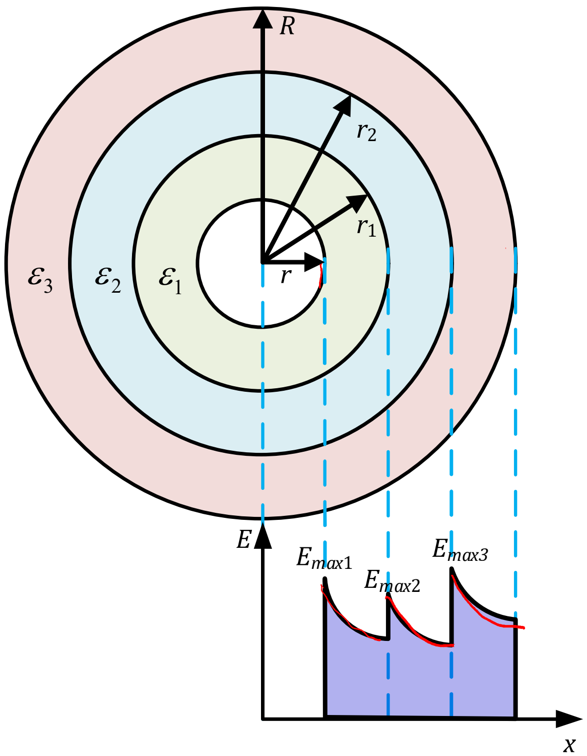
$$E_{\max 1} \neq E_{\max 2} \neq E_{\max 3}$$

Layer 1 (ε_1) $r < x < r_1$	
$E_1(x) = \dfrac{q}{2\pi\varepsilon_1 x}$	$E_{\max 1} = \dfrac{q}{2\pi\varepsilon_1 r}$

Layer 2 (ε_2) $r_1 < x < r_2$	
$E_2(x) = \dfrac{q}{2\pi\varepsilon_2 x}$	$E_{\max 2} = \dfrac{q}{2\pi\varepsilon_2 r_1}$

Layer 3 (ε_3) $r_2 < x < R$	
$E_3(x) = \dfrac{q}{2\pi\varepsilon_3 x}$	$E_{\max 3} = \dfrac{q}{2\pi\varepsilon_3 r_2}$

Capacitance Grading (With Different Maximum Stress)



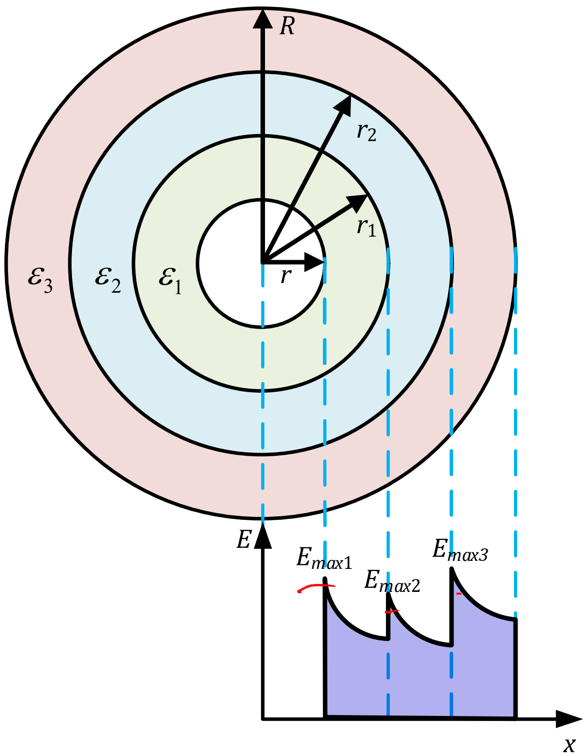
Layer 1 (ε_1) $r < x < r_1$	Layer 2 (ε_2) $r_1 < x < r_2$	Layer 3 (ε_3) $r_2 < x < R$
$E_1(x) = \frac{q}{2\pi\varepsilon_1 x}$ $E_{\max 1} = \frac{q}{2\pi\varepsilon_1 r}$ $E_{\max 1} 2\pi\varepsilon_1 r = q$	$E_2(x) = \frac{q}{2\pi\varepsilon_2 x}$ $E_{\max 2} = \frac{q}{2\pi\varepsilon_2 r}$ $E_{\max 2}\ 2\pi\varepsilon_2 r_1 = q$	$E_3(x) = \frac{q}{2\pi\varepsilon_3 x}$ $E_{\max 3} = \frac{q}{2\pi\varepsilon_3 r_2}$ $E_{\max 3}\ 2\pi\varepsilon_3 r_2 = q$

$$E_{\max 1}\ 2\pi\varepsilon_1 r = E_{\max 2}\ 2\pi\varepsilon_2 r_1 = E_{\max 3}\ 2\pi\varepsilon_2 r_2$$

$$E_{\max 1}\ \varepsilon_1 r = E_{\max 2}\ \varepsilon_2 r_1 = E_{\max 3}\ \varepsilon_2 r_2$$

- Since $r < r_1 < r_2$ ➡ $E_{\max 1}\varepsilon_1 > E_{\max 2}\varepsilon_2 > E_{\max 3}\varepsilon_2$
- Therefore material having highest product of permittivity and dielectric strength should be kept near to the conductor. The operating voltage of Cable is given by

Capacitance Grading (With Different Maximum Stress)



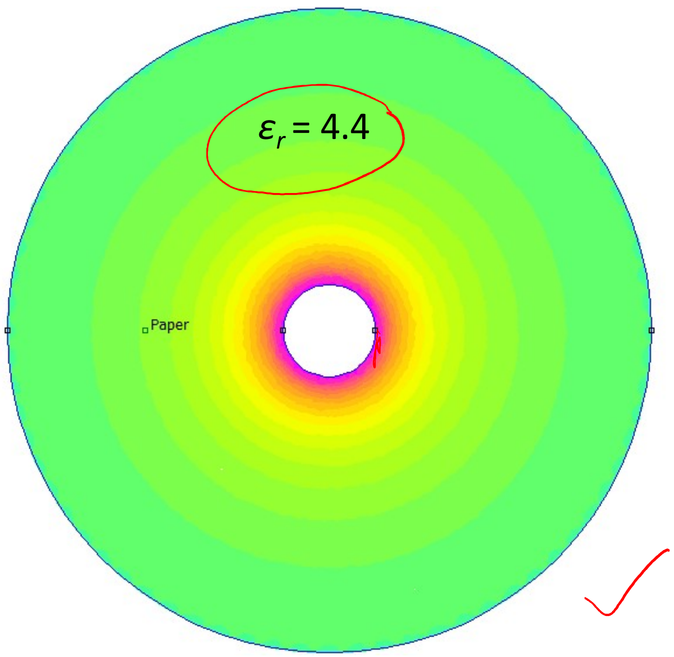
Layer 1 (ε_1) $r < x < r_1$	**Layer 2 (ε_2)** $r_1 < x < r_2$	**Layer 3 (ε_3)** $r_2 < x < R$
$E_1(x) = \dfrac{q}{2\pi\varepsilon_1 x}$	$E_2(x) = \dfrac{q}{2\pi\varepsilon_2 x}$	$E_3(x) = \dfrac{q}{2\pi\varepsilon_3 x}$
$E_{\max 1} = \dfrac{q}{2\pi\varepsilon_1 r}$	$E_{\max 2} = \dfrac{q}{2\pi\varepsilon_2 r_1}$	$E_{\max 2} = \dfrac{q}{2\pi\varepsilon_3 r_2}$

$$V = \int_r^{r_1} E_1\,dx + \int_{r_1}^{r_2} E_2\,dx + \int_{r_2}^{R} E_3\,dx$$

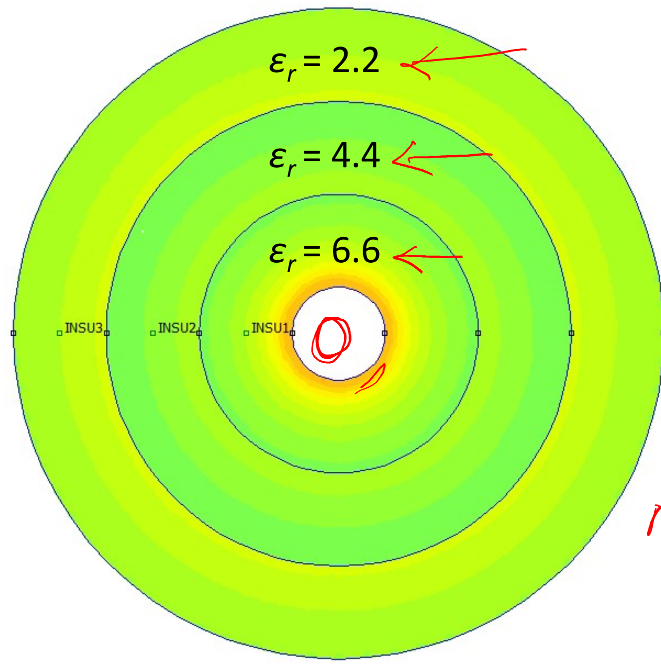
$$= \frac{q}{2\pi\varepsilon_1}\ln\frac{r_1}{r} + \frac{q}{2\pi\varepsilon_2}\ln\frac{r_2}{r_1} + \frac{q}{2\pi\varepsilon_1}\ln\frac{R}{r_2}$$

$$\boxed{V = \frac{q}{2\pi}\left(\frac{1}{\varepsilon_1}\ln\frac{r_1}{r} + \frac{1}{\varepsilon_2}\ln\frac{r_2}{r_1} + \frac{1}{\varepsilon_3}\ln\frac{R}{r_2}\right)}$$

Capacitance Grading



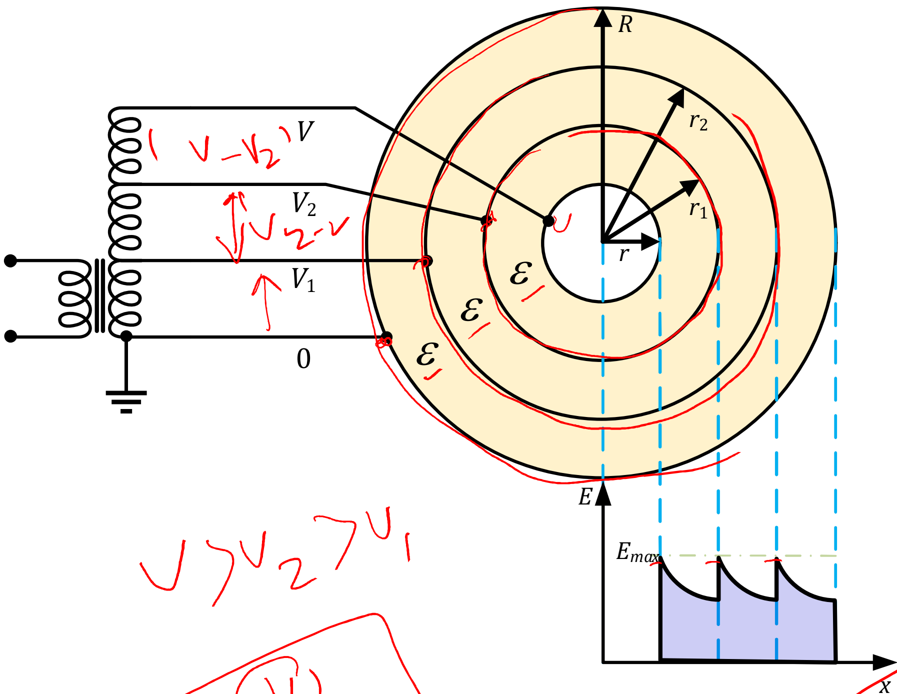
Without grading



Higher voltage

With capacitance grading

Intersheath Grading



$V > V_2 > V_1$

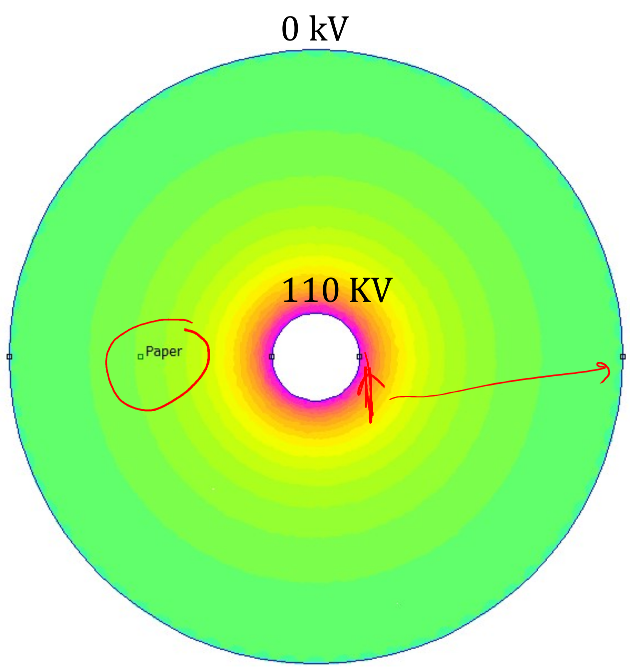
$\boxed{E = \frac{V}{x \ln \frac{R}{r}}}$

- Metal Sheaths having radii r_1 and r_2 are kept at potential V_1 and $V_{2.}$ using auxiliary transformer.

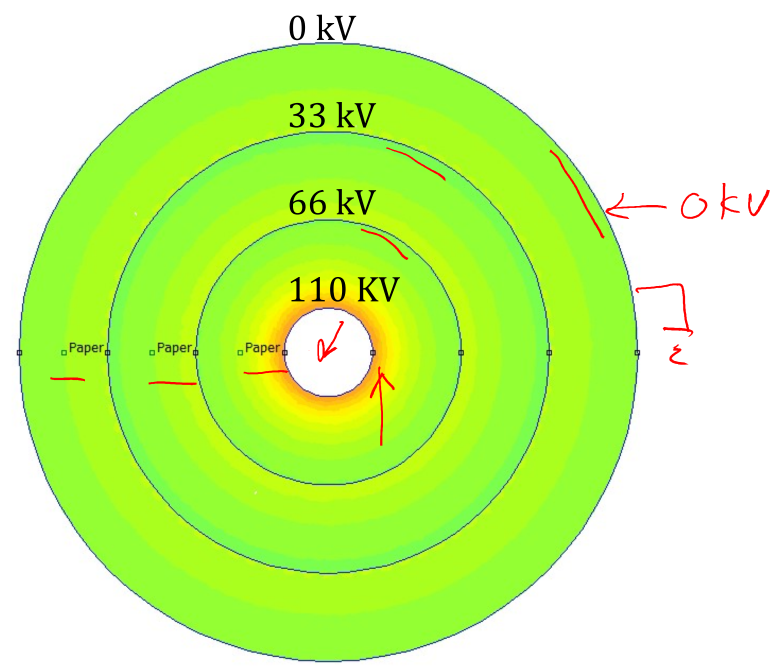
Layer 1 (V)	Layer 1 (V_1)	Layer 1 (V_2)
$E_{max} = \frac{V - V_2}{r \ln \frac{r_1}{r}}$	$E_{max} = \frac{V_2 - V_1}{r_1 \ln \frac{r_2}{r_1}}$	$E_{max} = \frac{V_1}{r_2 \ln \frac{R}{r_2}}$

$$\frac{V - V_2}{r \ln \frac{r_1}{r}} = \frac{V_2 - V_1}{r_1 \ln \frac{r_2}{r_1}} = \frac{V_1}{r_2 \ln \frac{R}{r_2}}$$

Intersheath Grading



Without grading

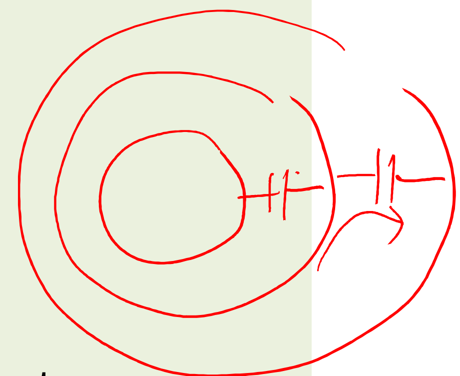


Intersheath grading

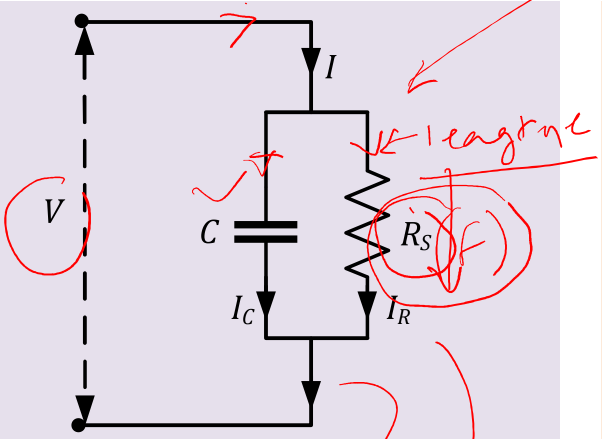
Grading of Cable

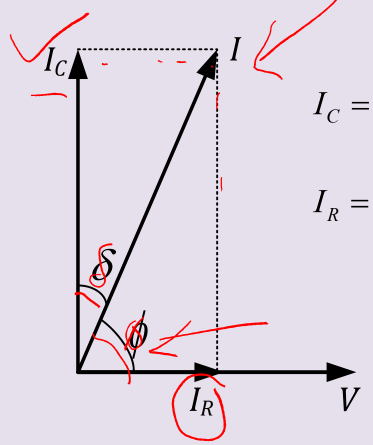
- **Usually not used commercially because of the following reasons:**
  - Non-availability of materials with required varying permittivity materials
  - There is change in permittivities of materials with time
  - The life spans of the materials are different

  - Damage of intersheath during cable laying
  - Charging current through the intersheath can damage the cable due to overheating



Dielectric Losses or Loss Tangent (tan δ)





$$I_C = \frac{V}{X_C}$$

$$I_R = \frac{V}{R_S}$$

- Power loss in leakage resistance

$$P_d = \frac{V^2}{R_s} = V\left(\frac{V}{R_s}\right)$$

- For small angle δ — radian

$$\delta \approx \tan\delta = \sin\delta = \sin(90-\phi) = \cos\phi$$

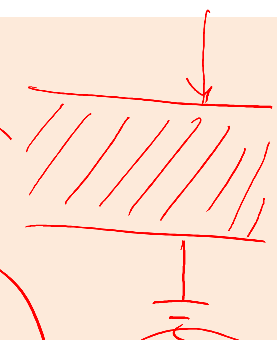
power factor

- From phasor diagram

$$\frac{I_R}{I_C} = \frac{V/R_s}{V/X_C} = \frac{V/R_s}{V\omega C} = \tan\delta \;\Rightarrow\; \frac{V}{R_s} = V\omega C \tan\delta$$

- Therefore, dielectric power loss: — radian

$$P_d = V^2\omega C \tan\delta = V^2\omega C\,\delta \;\; \text{W/km} \quad (1)$$



Breakdowns in Cable Insulation

- **Intrinsic Breakdown or puncture**

few msec

  - When an electric field is applied, electrons gain energy from the electric field and cross the forbidden energy gap from the valence band to the conduction band.
  - When this process is repeated, more and more electrons become available in the conduction band, eventually leading to breakdown.
  - Conduction electrons gain sufficient energy above a certain critical electric field and cause liberation of electrons from the lattice atoms by collision.

- **Thermal Breakdown**

hours

  - Equilibrium is reached when the heat used to raise the temperature of the dielectric, plus the heat dissipated, equals the heat generated.
  - Breakdown occurs when heat generated exceeds heat dissipated.

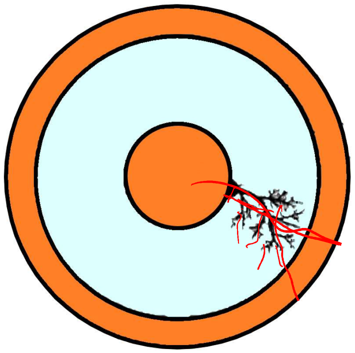
losses

$$I^2R = Q_C + Q_R + mC_P\frac{dT}{dt}$$

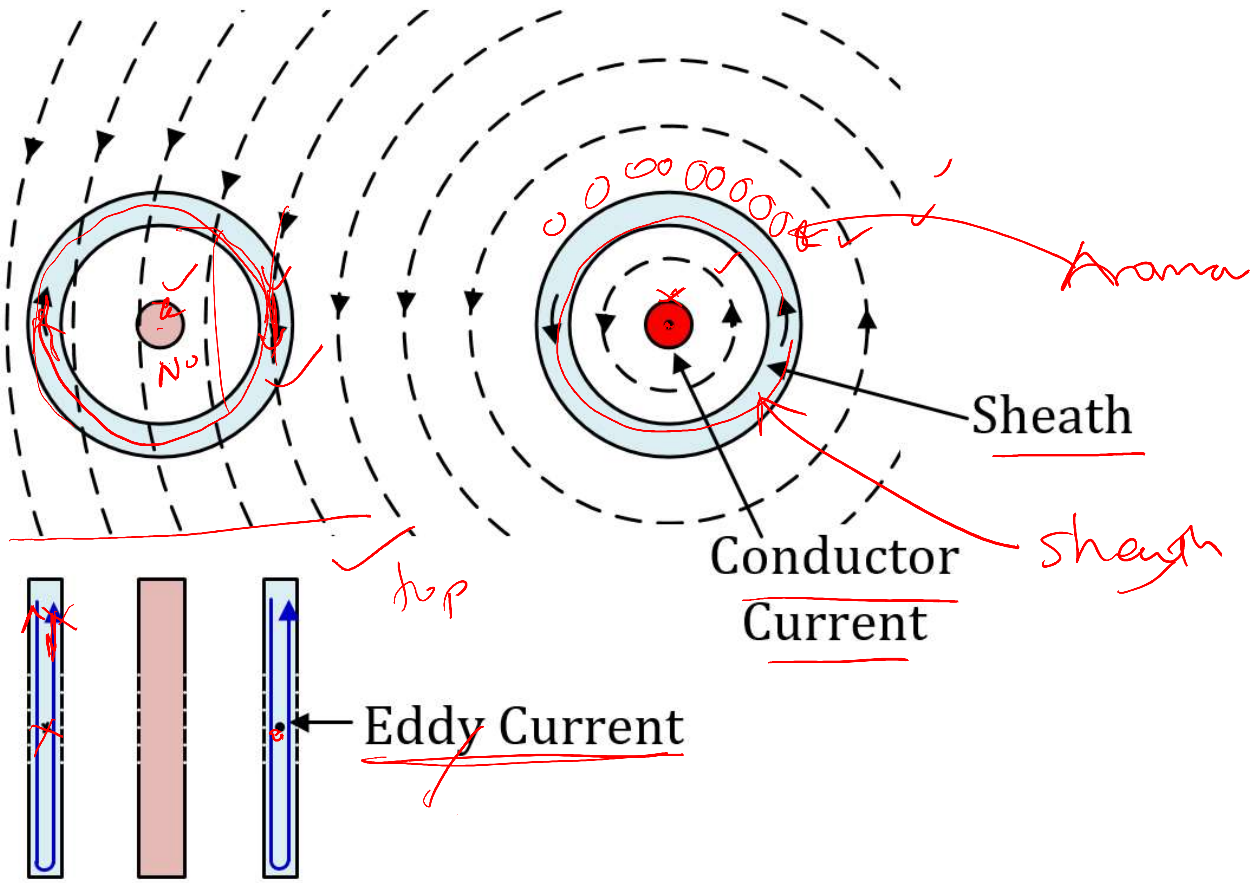
- **Treeing**

years

  - When the breakdown occurs in the voids, electrons and positive ions are formed.
  - They will have sufficient energy and when they reach the void surfaces they may break the chemical bonds.
  - Also, in each discharge there will be some heat dissipated in the cavities, and this will carbonize the surface of the voids and will caused erosions of the material.



Sheath and Armor losses



Thank You