Capacitance of 3-Core Cables

- The capacitance of a cable system is much more important than that of overhead line because in cables (*i*) conductors are nearer to each other and to the earthed sheath (*ii*) they are separated by a dielectric of permittivity much greater than that of air.
- Figure 16 shows a system of capacitances in a 3-core belted cable used for 3-phase system. Since potential difference exists between pairs of conductors and between each conductor and the sheath, electrostatic fields are set up in the cable as shown in Fig. 16 (*i*).
- These electrostatic fields give rise to core-core capacitances C_c and conductor-earth capacitances C_e as shown in Figure 16(*ii*).
- The three C_c are delta connected whereas the three C_e are star connected, the sheath forming the star point as shown in Figure 16 (*iii*).

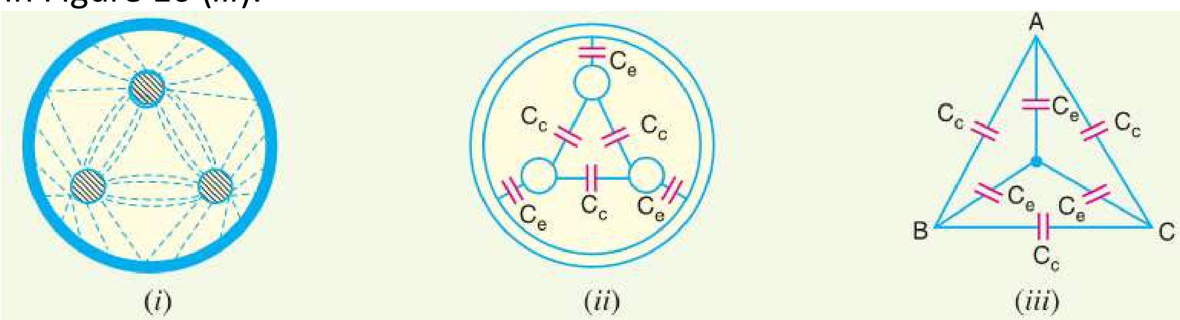


Figure 16

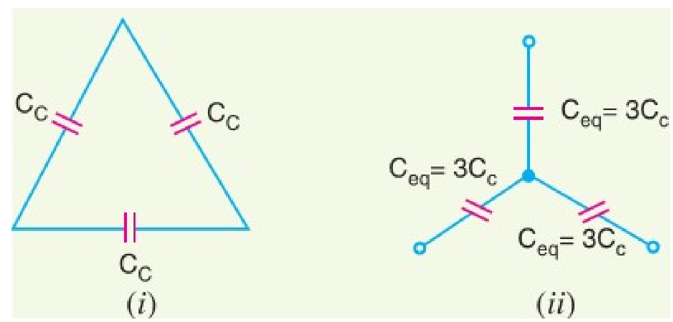


Figure 17

- They lay of a belted cable makes it reasonable to assume equality of each C_c and each C_e. The three delta connected capacitances C_c as shown in Figure 17 (*i*) can be converted into equivalent star connected capacitances as shown in Fig. 17(*ii*). It can be easily shown that equivalent star capacitance C_{eq} is equal to three times the delta capacitance C_c *i.e.* $C_{eq} = 3C_c$.

Capacitance of 3-Core Cables

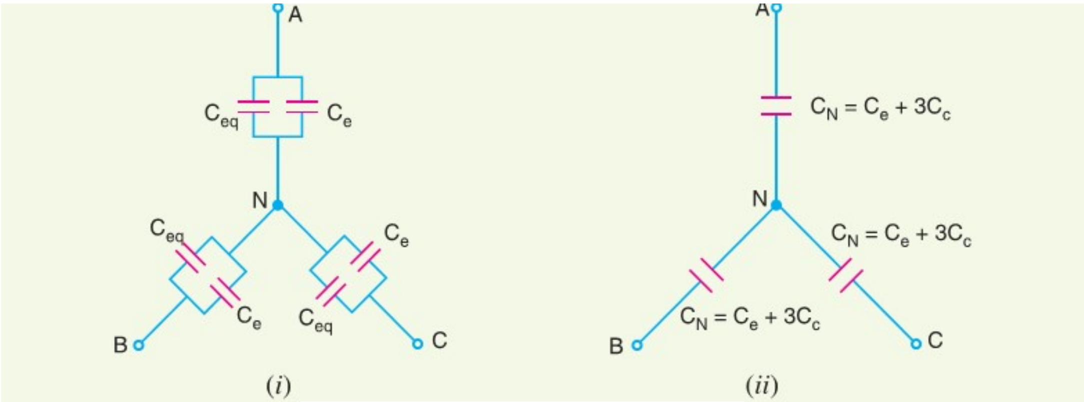


Figure 18

- Figure 16 (*iii*) reduces to the equivalent circuit shown in Figure 17 (*i*). Therefore, the whole cable is equivalent to three star-connected capacitors each of capacitance $C_N = C_e + C_{eq} = C_e + 3Cc$

- If V_{ph} is the phase voltage, then charging current I_C is given by:
$$I_C = V_{ph}/\ Capacitive\ reactance\ per\ phase\ = 2\pi f V_{ph} C_N\ = 2\pi f V_{ph}(C_e + 3Cc)$$

Measurements of C_e and C_c

- Although core-core capacitance C_c and core-earth capacitance C_e can be obtained from the empirical formulas for belted cables, their values can also be determined by measurements.
- For this purpose, the following two measurements are required:

(*i*) In the first measurement, the three cores are bunched together (*i.e.* commoned) and the capacitance is measured between the bunched cores and the sheath. The bunching eliminates all the three capacitors C_c, leaving the three capacitors C_e in parallel. Therefore, if C_1 is the measured capacitance, this test yields: $C_1 = 3Ce$ or $C_e = C_1/3$. Knowing the value of C_1, the value of C_e can be determined.

(*ii*) In the second measurement, two cores are bunched with the sheath and capacitance is measured between them and the third core. This test yields $2Cc + Ce$. If C_2 is the measured capacitance, then, $C_2 = 2Cc + Ce$. As the value of C_e is known from first test and C_2 is found experimentally, therefore, value of C_c can be determined.

- It may be noted here that if value of C_N $(= \ C_e \ + \ 3Cc)$ is desired, it can be found directly by another test. In this test, the capacitance between two cores or lines is measured with the third core free or connected to the sheath. This eliminates one of the capacitors C_e so that if C_3 is the measured capacitance, then,

$$C_3 = CC + \frac{C_C}{2} + \frac{C_e}{2} = \frac{1}{2}(Ce + 3CC) = \frac{1}{2}C_N$$

Types of Cable Faults

- Cables are generally laid directly in the ground or in ducts in the underground distribution system. For this reason, there are little chances of faults in underground cables. However, if a fault does occur, it is difficult to locate and repair the fault because conductors are not visible. Nevertheless, the following are the faults most likely to occur in underground cables :
  - **(i) Open-circuit fault**
  - **(ii) Short-circuit fault**
  - **(iii) Earth fault.**

(*i*) ***Open-circuit fault*:-** When there is a break in the conductor of a cable, it is called open circuit fault. The open-circuit fault can be checked by a megger. For this purpose, the three conductors of the 3-core cable at the far end are shorted and earthed. Then resistance between each conductor and earth is measured by a megger. The megger will indicate zero resistance in the circuit of the conductor that is not broken. However, if the conductor is broken, the megger will indicate infinite resistance in its circuit.

(*ii*) ***Short-circuit fault:-*** When two conductors of a multi-core cable come in electrical contact with each other due to insulation failure, it is called a short-circuit fault. Again, we can seek the help of a megger to check this fault. For this purpose, the two terminals of the megger are connected to any two conductors. If the megger gives zero reading, it indicates short circuit fault between these conductors. The same step is repeated for other conductors taking two at a time.

(*iii*) ***Earth fault:-*** When the conductor of a cable comes in contact with earth, it is called earth fault or ground fault. To identify this fault, one terminal of the megger is connected to the conductor and the other terminal connected to earth. If the megger indicates zero reading, it means the conductor is earthed. The same procedure is repeated for other conductors of the cable.

Permissible Current Loading

- The safe current-carrying capacity of an underground cable is determined by the maximum permissible temperature rise. The cause of temperature rise is the losses that occur in a cable which appear as heat. These losses are :

  (*i*) Copper losses in the conductors
  (*ii*) Hysteresis losses in the dielectric
  (*iii*) Eddy current losses in the sheath
- The safe working conductor temperature is 65ºC for armoured cables and 50ºC for lead-sheathed cables laid in ducts.
- The maximum steady temperature conditions prevail when the heat generated in the cable is equal to the heat dissipated.
- The heat dissipation of the conductor losses is by conduction through the insulation to the sheath from which the total losses (including dielectric and sheath losses) may be conducted to the earth.
- Therefore, in order to find permissible current loading, the thermal resistivities of the insulation, the protective covering and the soil must be known.

Permissible Current Loading

- When considering heat dissipation in underground cables, the various thermal resistances providing a heat dissipation path are in series. Therefore, they add up like electrical resistances in series.
- Consider a cable laid in soil.
- Let I = permissible current per conductor
- n = number of conductors
- R = electrical resistance per metre length of the conductor at the working temperature
- S= total thermal resistance (*i.e.* sum of thermal resistances of dielectric and soil) per metre length
- t = temperature difference (rise) between the conductor and the soil
- Neglecting the dielectric and sheath losses, we have,

$$Power\ dissipated\ =\ nI^2R$$

$$Power\ dissipated\ =\ Temperature\ rise/Thermal\ resistance$$

or, $nI^2R = \frac{t}{S}$ $\left[S = \frac{Resistivity}{2\pi} ln\left(\frac{d_1}{d}\right)\ Thermal\ ohm\ per\ meter\right]$

or, $I = \sqrt{\frac{t}{nRS}}$

It should be noted that when cables are laid in proximity to each other, the permissible current is reduced further on account of mutual heating.

Dielectric Loss

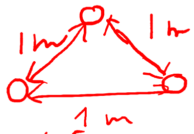
- Dielectrics (insulating materials for example) when subjected to a varying electric field, will have some energy loss.
- The varying electric field causes small realignment of weakly bonded molecules, which lead to the production of heat.
- The amount of loss increases as the voltage level is increased. For low voltage cables, the loss is usually insignificant and is generally ignored.
- For higher voltage cables, the loss and heat generated can become important and needs to be taken into consideration.
- Dielectric loss is measured using what is known as the loss tangent or tan delta ($\tan\delta$).
- In simple terms, tan delta is the tangent of the angle between the alternating field vector and the loss component of the material. The higher the value of $\tan\delta$ the greater the dielectric loss will be.
- Given the tan δ and capacitance of the cable, the dielectric loss is easily calculated:

  $$Loss = \omega C V^2 tan\delta$$

Problem:- *A 3-phase line has conductors 2 cm in diameter spaced equilaterally 1 m apart. If the dielectric strength of air is 30 kV (max) per cm, find the critical disruptive voltage for the line. Take air density factor δ = 0·952 and irregularity factor m_0 = 0·9.*

$r = 1\,cm$

$d = 100\,cm$



$g_0 = \frac{30}{\sqrt{2}} = 21\cdot 2\,kV\,(rms)/cm$

$\delta = 0\cdot 952$

$m_0 = 0\cdot 9$

$V_c = m_0 g_0 \delta r \cdot \ln\left(\frac{d}{r}\right)$ GMD

cm

$V_c = 0\cdot 9 \times 21\cdot 2 \times 0\cdot 952 \times 1 \times \ln\left(\frac{100}{1}\right)$ kV

$= 83\cdot 6490\,kV \longrightarrow$ phase voltage

$(V_c)_{Line} = \sqrt{3}\,V_c$

$= 144\cdot 8844\,kV$

Problem:-*A 132 kV line with 1·956 cm dia. conductors is built so that corona takes place if the line voltage exceeds 210 kV (r.m.s.). If the value of potential gradient at which ionisation occurs can be taken as 30 kV per cm, find the spacing between the conductors.*

$g_0 = 21.2$ kV (rms)/cm

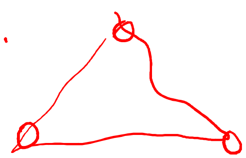
$m_0 = 1$

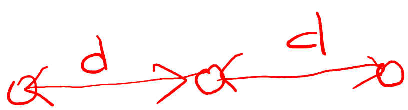
$\delta = 1$

$r = \frac{1.956}{2}$ cm $= 0.978$ cm

$d = ?$

$V_c = \frac{210}{\sqrt{3}}$ kV $= 121.2435$ kV





GMD =

$$121.2435 = 1 \times 21.2 \times 1 \times 0.978 \times \ln\left(\frac{d}{0.978}\right)$$

$$\ln\left(\frac{d}{0.978}\right) = \frac{121.2435}{(21.2 \times 0.978)}$$

$$= 5.8477$$

$$\frac{d}{0.978} = e^{(5.8477)}$$

$$d = 0.978 \times e^{(5.8477)}$$

$$= \underline{338.815 \text{ cm}}$$

Problem:-Certain 3-phase equilateral transmission line has a total corona loss of 53 kW at 106 kV and a loss of 98 kW at 110·9 kV. What is the critical disruptive voltage? What is the corona loss at 113 kV?

$$P_{Loss} = 3\times\left[242.2\,\frac{(f+25)}{\delta}\sqrt{\frac{r}{d}}\,(V-V_c)^2\times10^{-5}\right]\ \text{kW/km}$$

$$P_{Loss} \propto (V-V_c)^2$$

$P_{Loss} = 53\,kW \Rightarrow 106\,kV$

$P_{loss} = 98\,kW \Rightarrow 110.9\,kV$

$P_{loss} = \ ? \Rightarrow 113\,kV$

$V_c = \ ??$

$$\frac{106}{\sqrt{3}} = 61.2\,kV$$

$$\frac{110.9}{\sqrt{3}} = 64.028\,kV$$

$$\frac{113}{\sqrt{3}} = 65.24\,kV$$

$$53 \Leftarrow P_{Loss} \propto (61.2 - V_c)^2 \quad — (1)$$

$$98\ \cancel{106} \Leftarrow P_{Loss} \propto (64.028 - V_c)^2 \quad — (2)$$

$$\frac{53}{98\ \cancel{106}} = \frac{(61.2 - V_c)^2}{(64.028 - V_c)^2}$$

$$\frac{61.2 - V_c}{64.028 - V_c} = \sqrt{\frac{53}{98}}$$

$$V_c = 53.35\,kV$$

$$113\,kV \Leftarrow P_{Loss} \propto (65.24 - 53.35)^2 \quad — (3)$$

$$\frac{53}{P_{Loss}} = \frac{(61.2 - 53.35)^2}{(65.24 - 53.35)^2}$$

$P_{Loss} = 121.5906$ kW.

Problem:-_Estimate the corona loss for a three-phase, 110 kV, 50 Hz, 150 km long transmission line consisting of three conductors each of 10 mm diameter and spaced 2·5 m apart in an equilateral triangle formation. The temperature of air is 30ºC and the atmospheric pressure is 750 mm of mercury. Take irregularity factor as 0·85. Ionisation of air may be assumed to take place at a maximum voltage gradient of 30 kV/ cm._

$r = 0.5\,cm$

$d = 250\,cm$

$t = 30°C$

$b = 75\,cm$ of Hg Column

$m_o = 0.85$

$g_o = 21.2\,kV(rms)/cm.$

$$\delta = \frac{3.92b}{273+t}$$

$$\delta = \frac{3.92 \times 75}{303}$$

$$= 0.9703$$

$$V_c = 0.85 \times 21.2 \times 0.9703 \times 0.5 \ln\left(\frac{250}{0.5}\right)$$

$$= 54.3306\,kV.$$

P_{Loss}/km/phase

$$= 242.2 \times \left(\frac{50+25}{0.9703}\right)\sqrt{\frac{0.5}{250}}\left(\frac{110}{\sqrt{3}} - 54.3306\right)^2 \times 10^{-5}\ kW$$

$$= 0.7052\,kW.$$

$$P_{Loss}/\text{phase} = (0.7052 \times 150)\,kW$$

$$= 105.7852\,kW.$$

$$\text{Total } P_{Loss} = 3 \times 105.7852\,kW$$

$$= 317.34\,kW$$

V_p/V_c	0·6	0·8	1·0	1·2	1·4	1·6
F	0·012	0·018	0·05	0·08	0·3	1·0

Determine the insulation resistance of a single-core cable of length 3 km and having conductor radius 12·5 mm, insulation thickness 10 mm and specific resistance of insulation of 5 × 10^{12}Ωm.

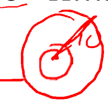
$$R = \frac{\rho}{2\pi L} \ln\left(\frac{r_2}{r_1}\right)$$

$$= \frac{5 \times 10^{12}}{2\pi \times 3 \times 10^3} \ln\left(\frac{22 \cdot 5}{12 \cdot 5}\right) \ \Omega$$

$$= 155915255 \cdot 3 \ \Omega$$

$$= 155 \cdot 9152 \ M\Omega$$

$R_{in} \propto \frac{1}{l}$



$R = \rho \frac{l}{A}$

$R \propto l$

An 11 kV, ~~50 Hz~~, single phase cable ~~2.5~~ km long, has a diameter of 20 mm and internal sheath radius of 15 mm. If the dielectric has a relative permittivity of 2.4, determine (*i*) capacitance (*ii*) charging current (*iii*) total charging kVAR.

$d = 20\,mm$

$D = 2 \times 15\,mm = 30\,mm$

$\epsilon_r = 2.4$

$\epsilon_0 = 8.854 \times 10^{-12}\,F/m$

$$C_T = \frac{2\pi \epsilon_0 \epsilon_r . l}{\ln\left(\frac{D}{d}\right)}$$

$$= \frac{2 \times \pi \times 8.854 \times 10^{-12} \times 2.4 \times 2.5 \times 10^3}{\ln\left(\frac{30}{20}\right)} F$$

$$= 8.2285 \times 10^{-7} F = 0.82285\,\mu f$$

$$(I_C)_{Line} = 11 \times 10^3 \times 2 \times \pi \times 50 \times 0.82285 \times 10^{-6} = 2.8436\,Amp$$

$3 V_{ph} I_{ph}$

$= ??$

$$3 \times \frac{V}{\sqrt{3}} \frac{(I_C)_{Line}}{\sqrt{3}} = 11 \times 10^3 \times 2.8436 = 31.279\,KVAR$$

A single core cable for use on 11 kV, 50 Hz system has conductor area of 0·645 cm² and internal diameter of sheath is 2·18 cm. The permittivity of the dielectric used in the cable is 3·5. Find (i) the maximum electrostatic stress in the cable (ii) minimum electrostatic stress in the cable (iii) capacitance of the cable per km length (iv) charging current.

$A_c = 0.645\,cm^2$

$\frac{\pi d^2}{4} = A_c$

$d = \sqrt{\frac{4A_c}{\pi}}$

$= \sqrt{\frac{4\times 0.645}{\pi}}$

$= 0.9062\,cm$

$D = 2.18\,cm$

$\epsilon_r = 3.5$

$g = \frac{V}{x \ln\left(\frac{D}{d}\right)}$

$\frac{D}{2}$

$g_{max} = \frac{2V}{d \ln\left(\frac{D}{d}\right)}$

$= 27.6562\,kV$

$g_{min} = \frac{2V}{D \ln\left(\frac{D}{d}\right)}$

$= 11.4963\,kV$

$C = \frac{2\pi \times 8.854\times 10^{-12} \times 3.5}{\ln\left(\frac{2.18}{0.9062}\right)}\,F$

$= 0.2218\,\mu f$

$\frac{D}{d}$

$I_c = 2\pi \times 50 \times 0.2218 \times 10^{-6} \times 11 \times 10^3$

$= 0.7664\,Amps.$

Find the most economical size of a single-core cable working on a 132 kV, 3-phase system, if a dielectric stress of 60 kV/cm can be allowed.

$g_{max} = 60\,kV/cm$

$$g_{max} = \frac{2V}{d \ln_e\left(\frac{D}{d}\right)}$$

$$= \frac{2V}{d}$$

$$60 \times 10^3 = \frac{2 \times 132 \times 10^3 \times \sqrt{2}}{\sqrt{3} \times d}$$

$$d = \frac{2 \times 132 \sqrt{2} \times 10^3}{\sqrt{3} \times 60 \times 10^3}\ cm$$

$$= 3.5926\ cm$$

$$\boxed{\frac{D}{d} = e}$$

d

$D = ed$

$= 9.7657\ cm$

The capacitances per kilometre of a 3-phase cable are 0·63μF between the three cores bunched together and the sheath and 0·37 μF between one core and the other two connected to the sheath. Calculate the charging current taken by eight kilometres of this cable when connected to a 3-phase, 50 Hz, 6600 V supply.

$3C_e = 0.63\mu f$

$C_e = 0.21\mu f$

$2C_c + C_e = 0.37\mu f$

$2C_c + 0.21 = 0.37$

$2C_c = 0.16\mu f$

$C_c = 0.08\mu f$

$C_N = 3C_c + C_e$

$= (0.24 + 0.21)\mu f$

$= 0.45\mu f$

$I_c = \frac{6600}{\sqrt{3}} \times 2 \times \pi \times 50 \times 0.45 \times 10^{-6} \times 8 \times 10^{3}$

$= 4.31$ Amp.

A single-core 66 kV cable has a conductor diameter of 2 cm and a sheath of inside diameter 5·3 cm. The cable has an inner layer of 1 cm thick of rubber of dielectric constant 4·5 and the rest impregnated paper of dielectric constant 3·6. Find the maximum stress in the rubber and in the paper.

$d = 2\,\text{cm}.$

$D = 5.3\,\text{cm}$

$\epsilon_1 = 4.5$

$\epsilon_2 = 3.6$

$d_1 = 4\,\text{cm}.$

$$g_{max} = \frac{Q}{2\pi\epsilon_0\epsilon_r x}.$$

$$g_{1max} = \frac{Q}{2\pi\epsilon_0\epsilon_1 \frac{d}{2}} \quad \text{— (1)}$$

$$g_{2max} = \frac{Q}{2\pi\epsilon_0\epsilon_2 \frac{d_1}{2}} \quad \text{— (2)}$$

$$\boxed{\frac{1}{\epsilon_1 \frac{d}{2}} = \frac{1}{\epsilon_2 \frac{d_1}{2}}}$$

$$\frac{g_{1max}}{g_{2max}} = \frac{\epsilon_2 d_1}{\epsilon_1 d} = \frac{3.6\times 4}{4.5\times 2} = \frac{7.2}{4.5}$$

$$g_{1max} = 1.6\, g_{2max}$$

$$g_{max} = \frac{2V_1}{d\ln\left(\frac{d_1}{d}\right)} \Rightarrow V_1 = \frac{d}{2} g_{1max} \ln\left(\frac{d_1}{d}\right)$$

$$g_{2max} = \frac{2V_2}{d_1\ln\left(\frac{D}{d_1}\right)} \Rightarrow V_2 = \frac{d_1}{2} g_{2max} \ln\left(\frac{D}{d_1}\right)$$

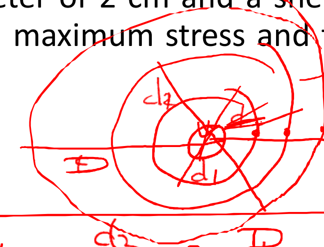
$66\times10^3/\sqrt{2}$

$$V = V_1 + V_2 = \frac{d}{2} g_{1max} \ln\left(\frac{d_1}{d}\right) + \frac{d_1}{2} g_{2max} \ln\left(\frac{D}{d_1}\right)$$

$g_{2max} = 39.476\,\text{kV/cm (rms)}$

$g_{1max} = 63.1631\,\text{kV/cm (rms)}.$

A single-core cable working on 66 kV on 3-phase system has a conductor diameter of 2 cm and a sheath of inside diameter 5·3 cm. If two intersheaths are used, find the best positions, maximum stress and the voltage on the intersheaths.



$d = 2\text{cm}.$

$D = 5.3\text{cm}.$

$d_1 = ?$

$d_2 = ?$

$$g_{1max} = \frac{2V_1}{d \ln\left(\frac{d_1}{d}\right)} \cong 39.0516 \text{ kV/cm (peak)}$$

$$g_{2max} = \frac{2V_2}{d_1 \ln\left(\frac{d_2}{d_1}\right)}$$

$$g_{3max} = \frac{2V_3}{d_2 \ln\left(\frac{D}{d_2}\right)}$$

g_{1min}
$= g_{2m}$
$= g_{m}$

$$\boxed{\frac{d_1}{d} = \frac{d_2}{d_1} = \frac{D}{d_2}}$$

$$\frac{d_1}{2} = \frac{d_2}{d_1} = \frac{5.3}{d_2}$$

$$d_1 d_2 = 10.6$$

$$d_1^2 = 2d_2$$

$$d_2 = \frac{d_1^2}{2}$$

$$\frac{d_1^3}{2} = 10.6$$

$$d_1 = 2.76 \text{ cm}$$

$$d_2 = \frac{d_1^2}{2} = 3.80884.$$

$$\frac{2V_1}{d \ln\left(\frac{d_1}{d}\right)} = \frac{2V_2}{d_1 \ln\left(\frac{d_2}{d_1}\right)} = \frac{2V_3}{d_2 \ln\left(\frac{D}{d_2}\right)}$$

$$\frac{2V_1}{2} = \frac{2V_2}{2.76} = \frac{2V_3}{3.8088}$$

$$V_3 = \frac{3.8088}{2} V_1$$

$$V_2 = \frac{2.76}{2} V_1$$

$$V_{int1} = V - V_1 = 41.3108\,2 \text{ kV (peak)}$$

$$V_{int2} = V - V_1 - V_2 = 23.91 \text{ kV (peak)}$$

$$V_1 + V_2 + V_3 = \frac{66\sqrt{2}}{\sqrt{3}}$$

$$V_1 = 12.5779 \text{ kV}.$$

$$V_2 = 17.39 \text{ kV}.$$