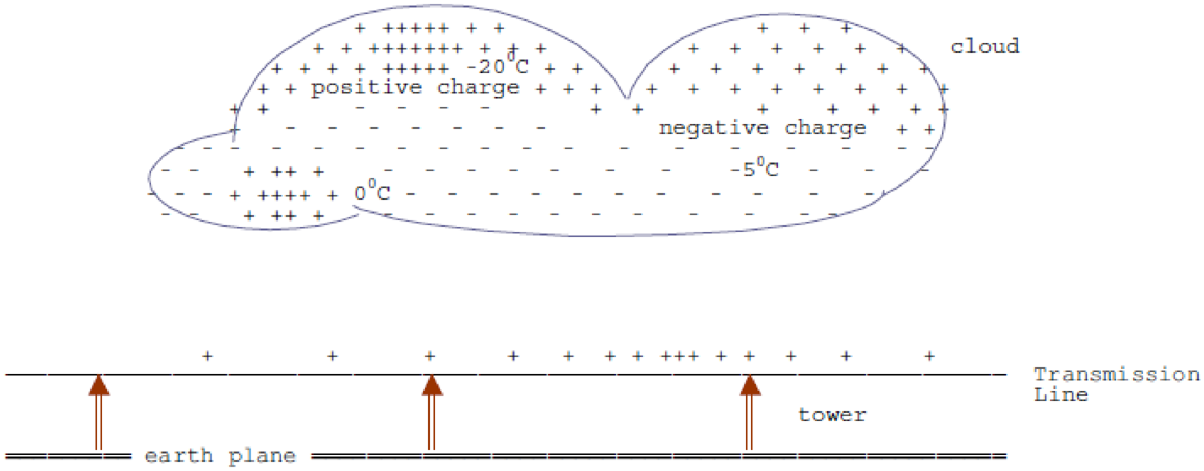
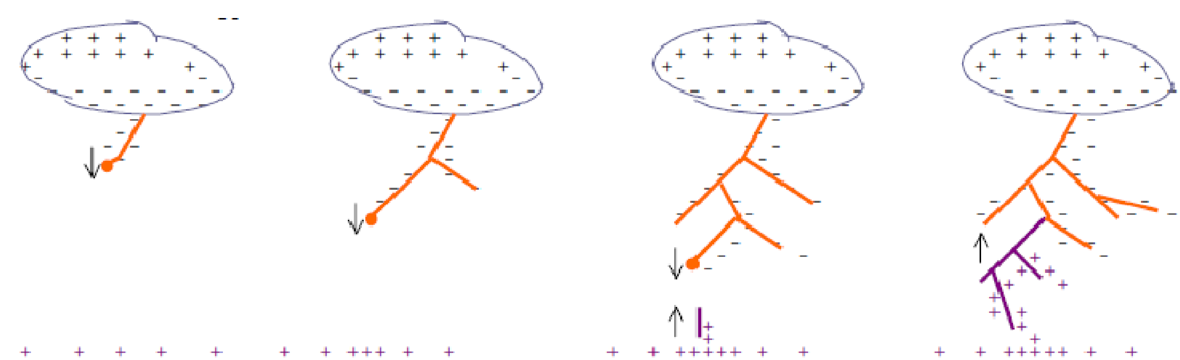
1 (a)

Figure shows a thundercloud cloud located above a overhead transmission line.



Under the influence of sufficiently strong fields, large water drops become elongated in the direction of the field and become unstable, and streamers develop at their ends with the onset of corona discharges. When the electric field in the vicinity of one of the negative charge centres builds up to the critical value (about 10 kV/cm), an ionized channel (or streamer) is formed, which propagates from the cloud to earth with a velocity that might be as high as one-tenth the speed of light. Usually this streamer is extinguished when only a short distance from the cloud. Forty micro-seconds or so after the first streamer, a second streamer occurs, closely following the path of the first, and propagating the ionised channel a little further before it is also spent. This process continues a number of times, each step increasing the channel length by 10 to 200 m. Because of the step like sequence in which this streamer travels to earth, this process is termed the **stepped leader**. This process is shown diagrammatically in the figure.



When the stepped leader has approached to within 15 to 50 m of the earth, the field intensity at earth is sufficient for an upward streamer to develop and bridge the remaining gap. A large **neutralising** current, termed the **return** stroke, flows along the ionised path, produced by the stepped leader with an average current of about 20 kA. The luminescence of the stepped leader decreases towards the cloud and in one instances it appears to vanish some distance below the cloud. This would suggest that the current is confined to the stepped leader itself. Following the first, or main stroke and after about 40 ms, a second leader stroke propagates to earth in a continuous and rapid manner and again a return stroke follows. This second and subsequent leader strokes which travel along the already energised channel are termed **dart leaders**.

What appears as a single flash of lightning usually consist of a number of successive strokes, following the same track in space, at intervals of a few hundredths of a second. The average number of strokes in a multiple stroke is four, but as many as 40 have been reported. The time interval between strokes ranges from 20 to 700 ms, but is most frequently 40-50 ms. The average duration of a complete flash being about 250 ms. The approximate time durations of the various components of a lightning stroke are summarised as follows.

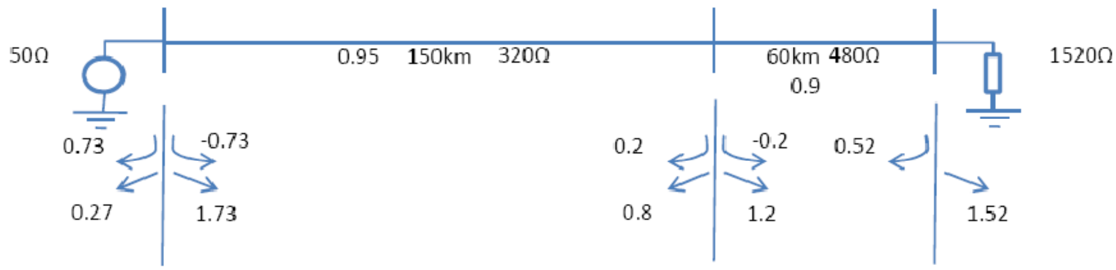
Stepped leader	= 10 ms
Return stroke	= 40 μs
period between strokes	= 40 ms
duration of dart leader	= 1 ms

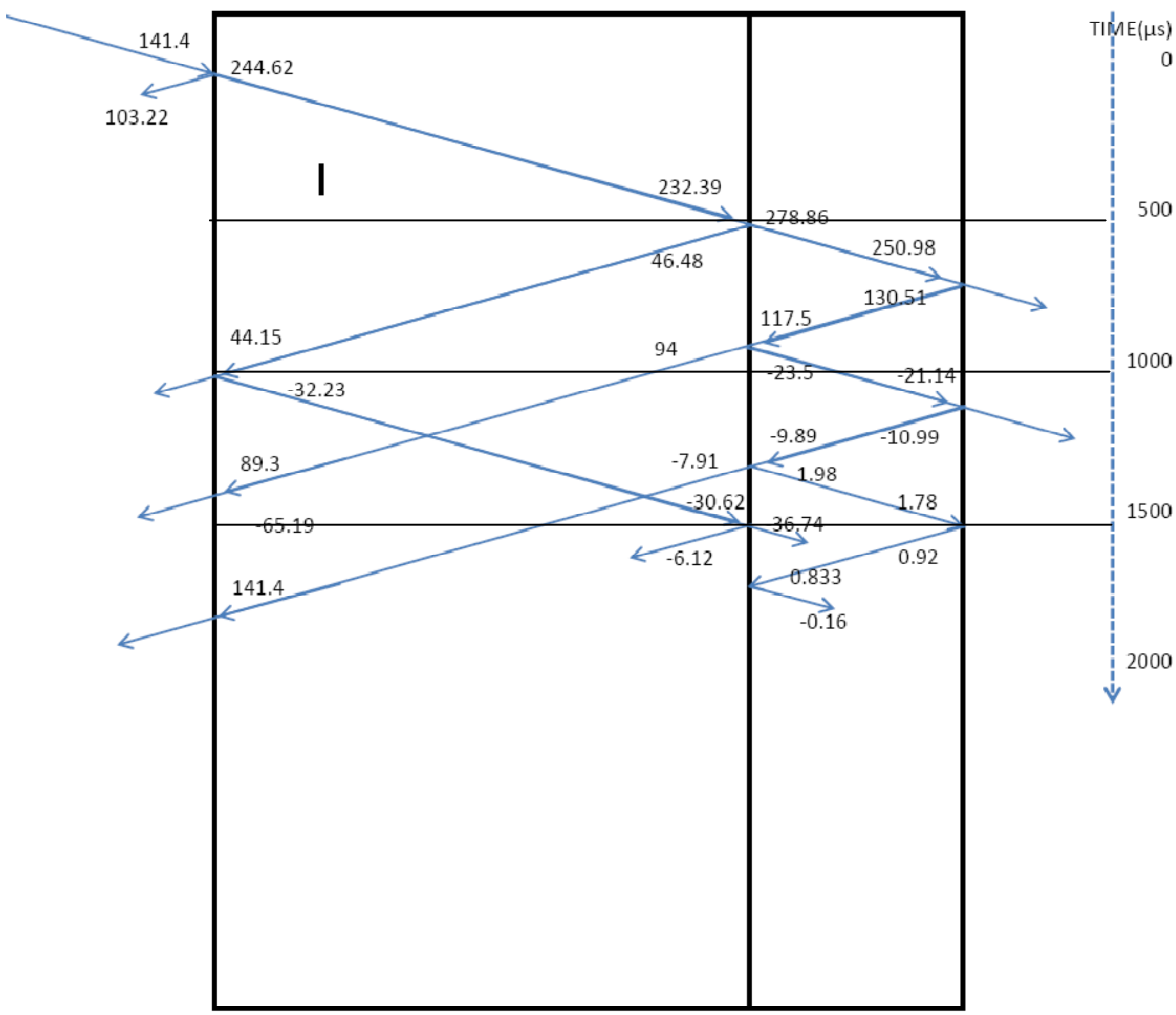
For the purpose of surge calculations, it is only the heavy current flow during the return stroke that is of importance.

1(b)

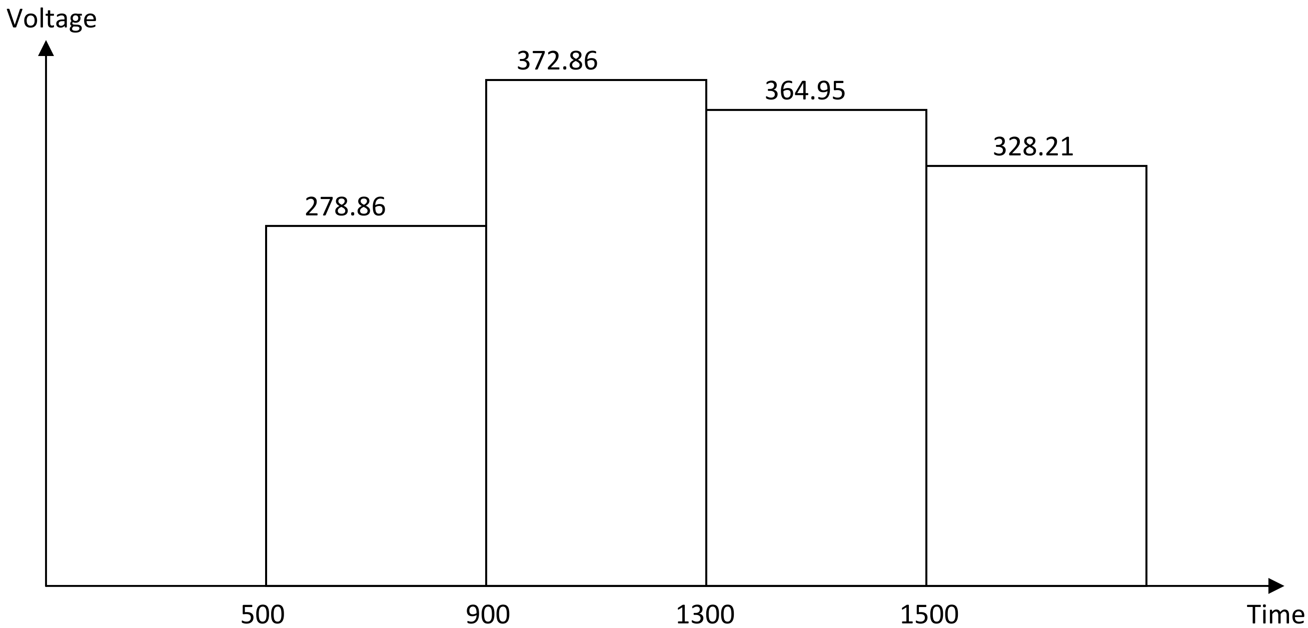
The traveling time of the surge from A-B = 150000/3x10⁸ = 500 μs

The traveling time of the surge from A-B = 60000/3x10⁸ = 200 μs





1 (c) Voltage at B is as follows for the period of first 1.5 ms.



The voltage at B in 1.5ms = (278.86) + (94) + (-7.91) +(-36.74) = 328.31 kV

1(d)

If the end C is open circuited, then the surge coming to the end C will completely reflected with a coefficient of unity.

Therefore,

The voltage at B in 1.5ms, with the enc C open circuited,

= (278.86)+(278.86 x $(0.9)^2$ x0.8) + (-278.86 x $(0.9)^4$ x 0.2 x 0.8) + (-36.74)

= 278.86+180.701-29.27 -36.74

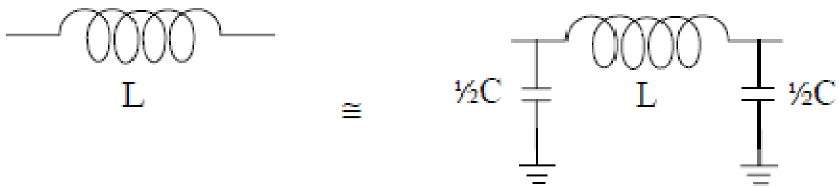
= 393.55 kV

2(a)

Inductances and capacitances could be represented, by considering them as very short lines or stub lines. This is done by assuming that an inductance has a distributed capacitance of negligible value to earth, and that shunt capacitances have a negligible series inductance. These assumptions will make the lumped elements stub lines with negligible transmission times.

It is usual to select the transmission times corresponding to the minimum time increment Δt or ½ Δt .

For the lumped inductance connected in series

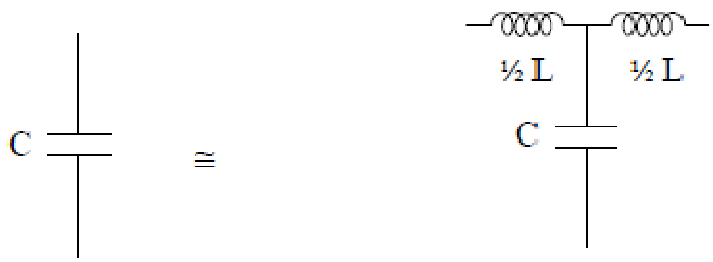


If the travel time of the line is selected corresponding to τ = Δt

$\tau = \sqrt{LC}$ so that $C = \frac{\tau^2}{L} = \frac{(\Delta t)^2}{L}$, $Z_0 = \sqrt{\frac{L}{C}} = \frac{L}{\tau} = \frac{L}{\Delta t}$

A lumped inductance may be represented by a stub line of transit time **Δt** and surge impedance **L/Δt**.

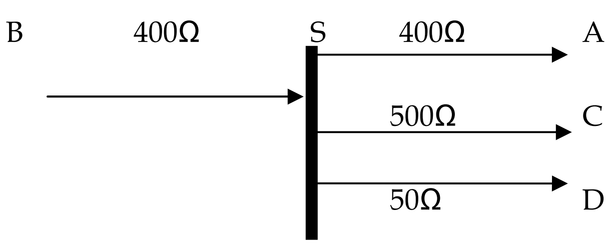
For the lumped capacitance connected in shunt

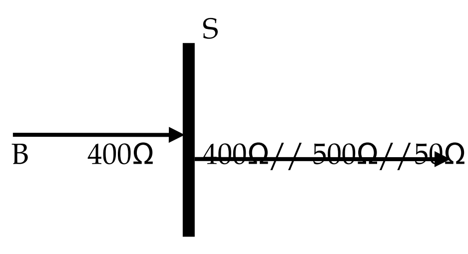


$\tau = \sqrt{LC}$ so that $L = \frac{\tau^2}{C} = \frac{(\Delta t)^2}{C}$, $Z_0 = \sqrt{\frac{L}{C}} = \frac{\tau}{C} = \frac{\Delta t}{C}$

A lumped capacitance may be represented by a stub line of transit time **Δt** and surge impedance **Δt/C**.

2(b)





Derivation of the equivalence of the above circuit as

Effective outgoing = 400//50//500 = 40.816Ω

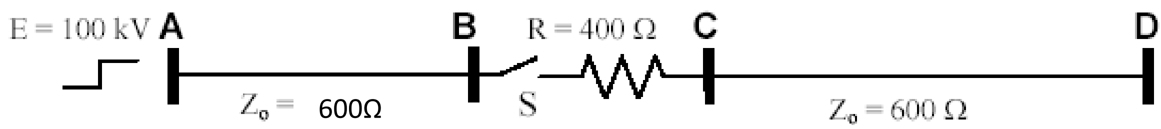
Reflection coefficient $= \frac{40.816 - 400}{400 + 40.816}$ = -0.8148

Transmission coefficient = 1− 0.816 = 0.184

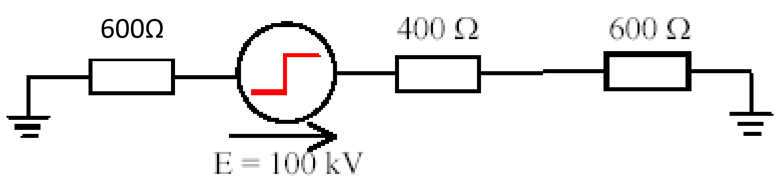
Voltage reflected to line SB = 100 x (-0.8148) = -81.48 kV

Voltage transmitted to line SD = 100 x 0.184 = 18.4 kV

2(c)



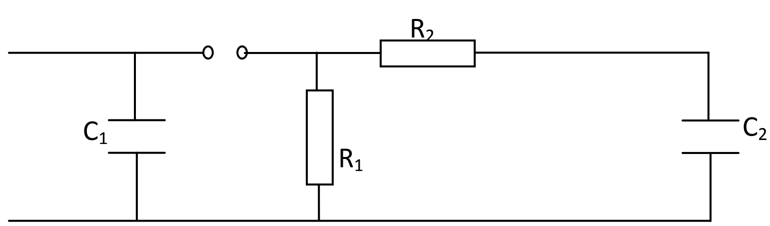
Prior to closure of switch, voltages are 100 kV at A and B, and 0 kV at C and D.
Voltage across S = 100 kV.
Since the relation between the surge voltage and surge current can be represented by V = Zo I, the closure of the switch can be represented and changes can be obtained from the equivalent circuit



3

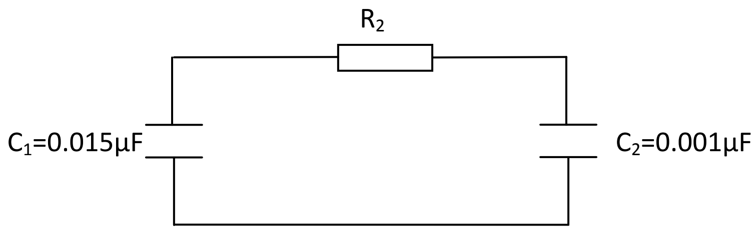
For the six stage impulse generator,

1) Let the reduced form of impulse generator



The per stage capacitance = 0.09µF
Therefore, C1= 0.09µF / 6 = 0.015µF
C2 = 1.2nF

2)



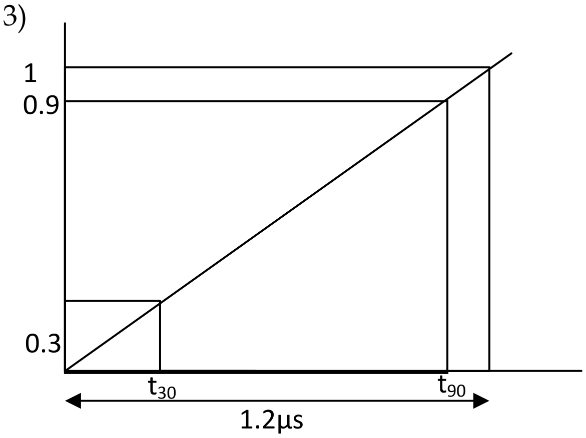
Here,

$$\frac{1}{\beta} = \frac{R_2 C_1 C_2}{C_1 + C_2}$$

$$n = \frac{C_1}{C_1 + C_2}$$

$$\frac{1}{\beta} = R_2 C_2 n$$

3)

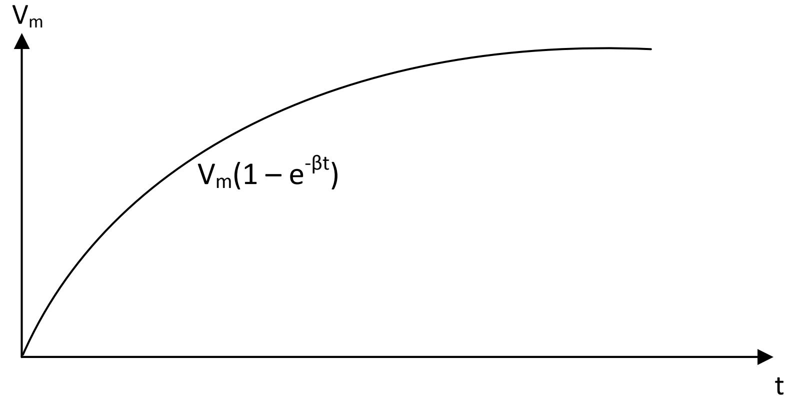


For standard wave form measured based on 30% & 90% for wave front

$$\frac{t_{90} - t_{30}}{0.9 - 0.3} = \frac{1.2}{1}$$

$$(t_{90} - t_{30}) = 0.72\ \mu s$$

4)



0.3V$_m$ = V$_m$ $(1 - e^{-\beta t_{30}})$

0.9V$_m$ = V$_m$ $(1 - e^{-\beta t_{90}})$

$0.7 \quad = e^{-\beta t_{30}}$

$0.1 \quad = e^{-\beta t_{90}}$

$\frac{0.7}{0.1} \quad = e^{\beta(t_{90} - t_{30})}$

$\ln 7 \quad = \beta(t_{90} - t_{30})$

$\beta \quad = \frac{\ln 7}{0.72} = 2.7\ \mu s^{-1}$

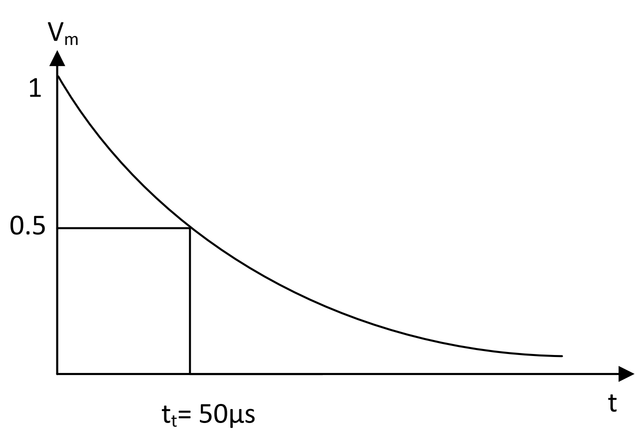
$\frac{1}{\beta} \quad = \frac{R_2 C_1 C_2}{C_1 + C_2}$

$R_2 \quad = \frac{\beta(C_1 + C_2)}{C_1 C_2}$

$\quad = \frac{2.7(0.015 + 0.0012)}{(0.015) * (0012)}$

R$_2$ = 333.33Ω

For wave tail considering a standard waveform

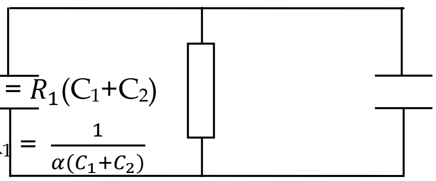


$V_m \quad = V_m e^{-\alpha t}$

$0.5V_m \quad = V_m e^{-\alpha t_t}$

$\alpha t_t \quad = \ln 2$

$\alpha \quad = \frac{ln2}{50} \quad = 0.01386\mu s^{-1}$



$\frac{1}{\alpha} = R_1(C_1+C_2)$

$R_1 = \frac{1}{\alpha(C_1+C_2)}$

$= \frac{1}{0.1386(0.015+0.0012)}$

$= 4453.7\Omega$

3 (c)

In practice, in addition to the main capacitors and inductors shown in the impulse generator circuit considered, stray capacitances will also be present. These will cause the order of the Laplace transform equation to become much higher and more complicated. Thus the actual waveform generated would be different and would contain superimposed fluctuations on the impulse waveform as shown.

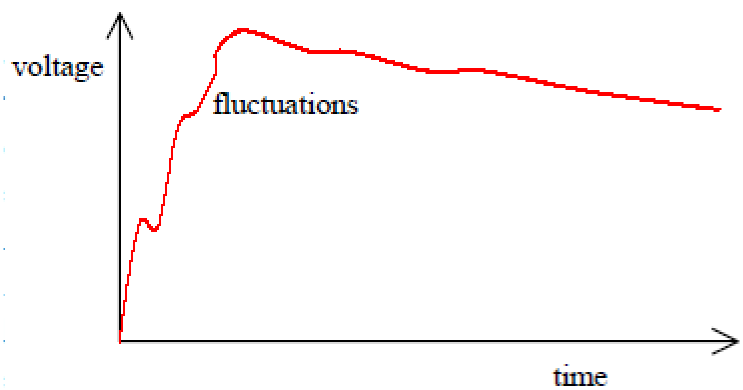
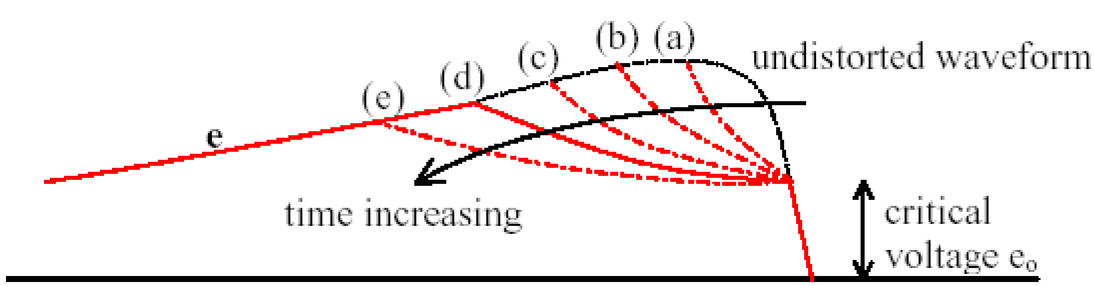


Figure 8.7 - Waveform with fluctuations

4(a)



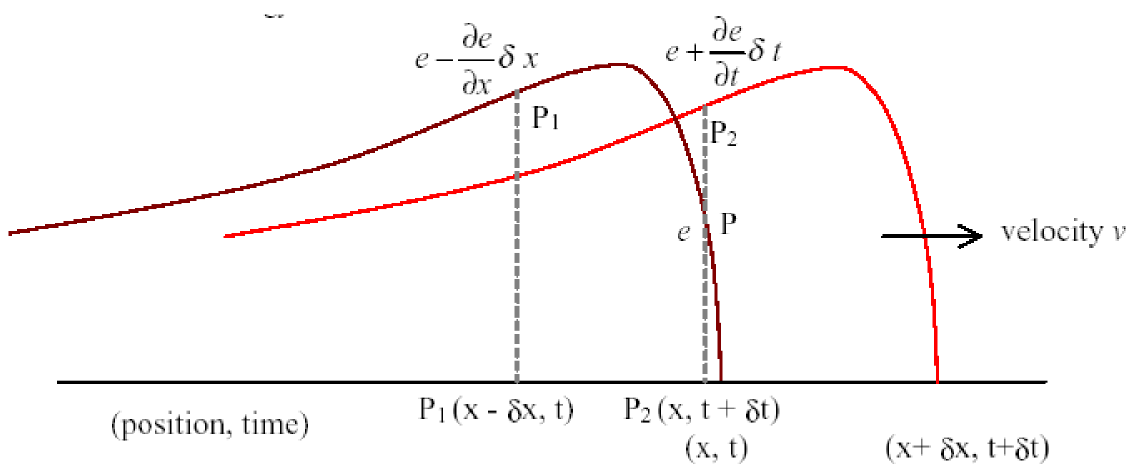
Corona thus reduces the steepness of the wavefront above the critical voltage, as the surge travels down the line. This means that energy is lost to the atmosphere.
Now consider the mathematical derivation.

Energy associated with a surge waveform = $\frac{1}{2}Ce^2 + \frac{1}{2}Li^2$

But the surge voltage **e** is related to the surge current **i** by the equation

$$i = \frac{e}{Z_0} = e\sqrt{\frac{C}{L}} \;\; , i.e. \;\; \frac{1}{2}Li^2 = \frac{1}{2}Ce^2$$

So that the total wave energy = Ce^2



Let the voltage at a point P at position **x** be **e** at time **t**.

Then voltage at point P1 just behind P would be $e - \frac{\partial e}{\partial x}\delta x$ at time t, or $e - \frac{\partial e}{\partial x}.v.\delta t$

If the voltage is above corona inception, it would not remain at this value but would attain a value
$e + \frac{\partial e}{\partial t}\delta t$

at P at time $t + \Delta t$ when the surge at P1 moves forward to P2.
Thus corona causes a depression in the voltage from $\left(e - \frac{\partial e}{\partial x}.v.\delta t\right)$ to $\left(e + \frac{\partial e}{\partial t}\delta t\right)$
with a corresponding loss of energy of $C\left[\left(e - v\frac{\partial e}{\partial x}\delta t\right)^2 - \left(e + \frac{\partial e}{\partial t}\delta t\right)^2\right]$ or $-2Ce\left[v\frac{\partial e}{\partial x} + \frac{\partial e}{\partial t}\right]\delta t$.
The energy to create a corona field is proportional to the square of the excess voltage. i.e. $k(e - e_0)^2$

Thus the energy required to change $\left(\mathrm{e} + \frac{\partial e}{\partial t}\delta t \right)$ the voltage from e to   is given by

$$k\left[\left(\mathrm{e} + \frac{\partial e}{\partial t}\delta t - e_0 \right)^2 - (e - e_0)^2\right] \;\; or \;\; 2k(e - e_0)\frac{\partial e}{\partial t}\delta t$$

The loss of energy causing distortion must be equal to the change in energy required. Thus

$$-2Ce\left[v\frac{\partial e}{\partial x} + \frac{\partial e}{\partial t}\right]\delta t = \; 2k(e - e_0)\frac{\partial e}{\partial t}.\delta t$$

Rearranging and simplifying gives the equation

$$v\frac{\partial e}{\partial x} = \; -\left[1 + \; \frac{k}{C}.\frac{(e - e_0)}{e}\right]\frac{\partial e}{\partial t}$$

Wave propagation under ideal conditions is written in the form

$$v\frac{\partial e}{\partial x} = \; -\frac{\partial e}{\partial t}$$

Thus we see that the wave velocity has decreased below the normal propagation velocity, and that the wave velocity of an increment of voltage at **e** has a magnitude given by

$$v_e = \frac{v}{1 + \frac{k}{C}\left(\frac{e - e_0}{e}\right)}$$

Thus the time of travel for an element at **e** when it travels a distance **x** is given by

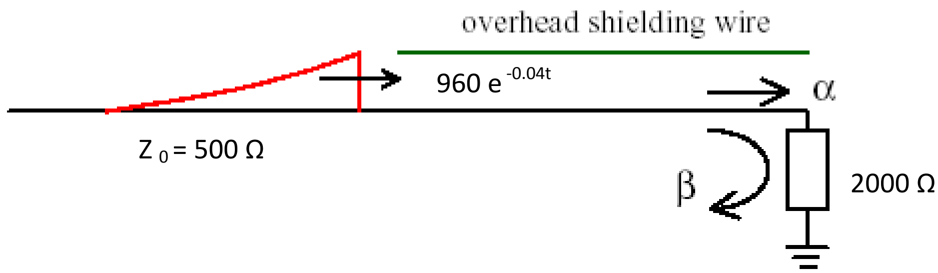
$$t = \; \frac{x}{v_e} = \; \frac{x}{v}\left[1 + \; \frac{k}{C}\left(\frac{e - e_0}{e}\right)\right]$$

$$i.e.\left[\frac{x}{v_e} - \frac{x}{v}\right] = \; \frac{x}{v}.\frac{k}{C}\left(\frac{e - e_0}{e}\right)$$

$\left[\frac{x}{v_e} - \frac{x}{v}\right]$is the Δt time lag corresponding to the voltage element at **e**. Thus

$\frac{\Delta t}{x} = \frac{k}{v.C}\left[1 - \frac{e_0}{e}\right]$

4. (b)



Transmission coefficient, $\alpha = \frac{2\times2000}{2000+500} = 1.6$

For a B.I.L of 1050 kV, and an insulation margin of 15%,

Maximum permissible voltage = 1050 x 85/100 = 892.5 kV.

Since the voltage is increased by the transmission coefficient 1.6 at the terminal equipment, the maximum permissible incident voltage must be decreased by this factor.

Thus maximum permissible incident surge = 892.5/ 1.6 = 557.8 kV
Thus for the transformer insulation to be protected by the shielding wire, the distortion caused must reduce the surge to a magnitude of 557.8 kV.

Therefore, $960\ e^{-0.04t} = 557.8$.

This gives the delay time t = 13.57 μs.

Substitution in the equation gives 13.57/x = (0.01) (1 - 300/557.8)
Solution gives x = 2936 m = 2.936 km.
Thus the minimum length of shielding wire required is 2.936 km.