UEE 403 – High Voltage Engineering – Answers – February 2004

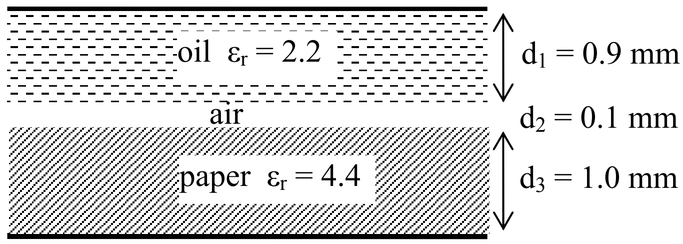
1. (a) Breakdown strength of air

= 30 kv/cm at NTP (assumption)

$\therefore$ to avoid partial discharges, max^{m} V

= $30 \times 10^3 \times 0.1/10 = 300$ V

same charge q = CV flows through all parts of the dielectric.

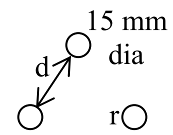


i.e. $V_1 : V_2 : V_3 = \frac{1}{C_1} : \frac{1}{C_2} : \frac{1}{C_3} = \frac{d_1}{A\varepsilon_1\varepsilon_o} : \frac{d_1}{A\varepsilon_2\varepsilon_o} : \frac{d_1}{A\varepsilon_3\varepsilon_o} = \frac{d_1}{\varepsilon_1} : \frac{d_1}{1} : \frac{d_1}{\varepsilon_3}$

i.e. $V_1.\frac{\varepsilon_1}{d_1} = V_2.\frac{1}{d_2} = V_3.\frac{\varepsilon_3}{d_3} \rightarrow V_1.\frac{2.2}{0.9} = 300.\frac{1}{0.1} = V_3.\frac{4.4}{1} \rightarrow$ V_1=1227.3V, V_2=300V, V_3=681.8V

$\therefore$ maximum voltage applicable = 1227.3 + 300V + 681.8 = 2209 = 2.2 kV

(b) 132 kV, 3 phase, 50 Hz, electric stress $\xi = \frac{V}{r \ln \frac{d}{r}}$



for air at NTP, ξ_{max}(peak) = 30 kV/cm

= $30/\sqrt{2}$ = 21.2 kV/cm rms

phase voltage of conductor = $132/\sqrt{3}$ = 76.21 kV

r = 15/2 mm = 0.75 cm

$\therefore$ corona inception voltage = 1.05×76.21 = 80.02 kV

i.e. $21.2 = \frac{80.02}{0.75 \ln \frac{d}{0.75}} \rightarrow 15.91 \ln \frac{d}{r} = 80.02$, d =114.65 cm = 1.15 m

(c) Description, with the aid of suitable diagrams, Bergeron's method of graphical solution

for a transmission line $-\frac{\partial v}{\partial x} = l\frac{\partial i}{\partial t}, \quad -\frac{\partial i}{\partial x} = c\frac{\partial v}{\partial t}$

which has the traveling wave solution

v = f(x-at) + F(x+at) where **a** is the wave velocity

$$-\frac{\partial i}{\partial x} = c\frac{\partial v}{\partial t} = c\,[\,-a\,f'(x-a\,t) + a\,F'(x+a\,t)]$$

$$\therefore\ i = a\,c\,[f\,(x-a\,t) - F\,(x+a\,t)], \quad \text{also } Z_0 = \sqrt{\frac{l}{c}} = \frac{1}{a\,c}$$

$$\text{i.e. } i\,Z_0 = f\,(x-a\,t) - F\,(x+a\,t)$$

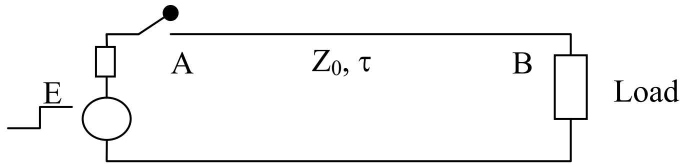
$$\therefore\ v - i\,Z_0 = 2\,F\,(x+a\,t), \quad v + i\,Z_0 = 2\,f\,(x-a\,t)$$

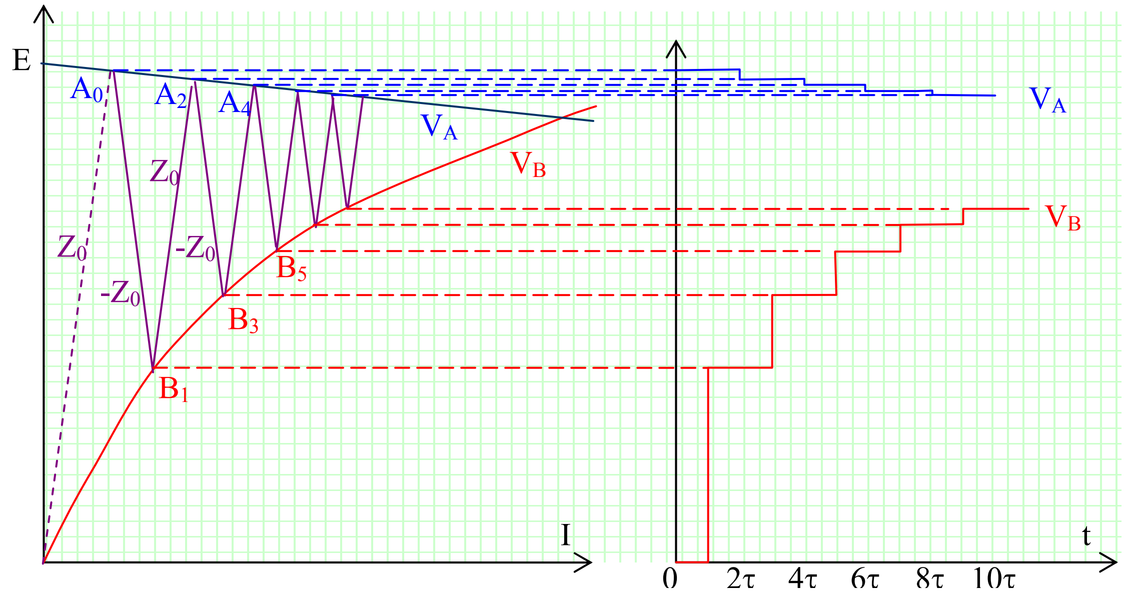
f(x-at) = constant represents a **forward traveling wave**,
and **F(x+at) = constant** represents a **backward traveling wave**.

From the expressions derived above, it can be seen that **v + Z_0 i = constant** represents a **forward wave** and **v - Z_0 i = constant** represents a **backward wave**.
In either case, value of constant is determined from the history of the wave up to that time.

The Bergeron's method is applied on a **voltage-current** diagram.

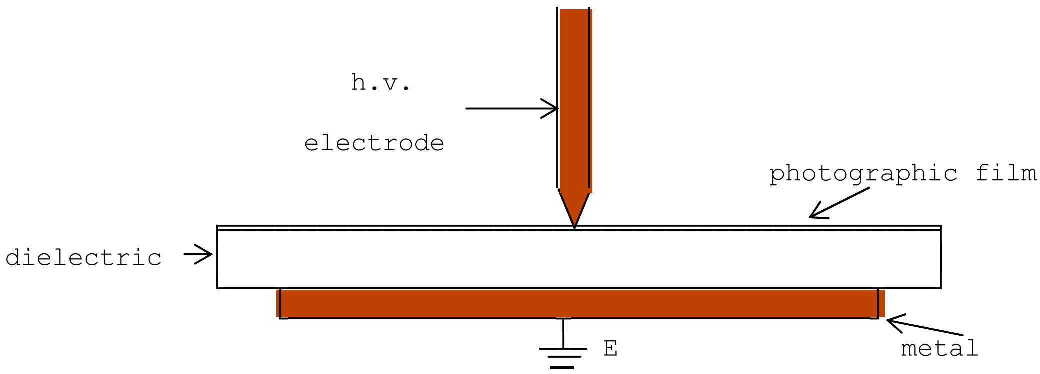
Consider the illustration





The initial point A_0 is obtained from the source characteristic and the surge impedance Z_0 corresponding to the first surge. Thereafter successive reflections at B and A are considered by lines with slope $-Z_0$ and Z_0 respectively. The voltage waveform can be projected and obtained as shown.

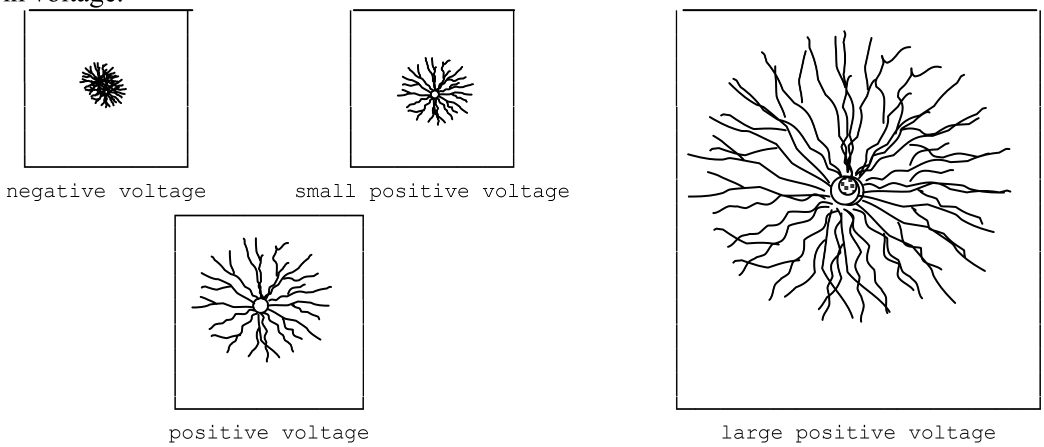
(d) Brief description of the Klydonograph.



The Klydonograph has a dielectric sheet, on the surface of which is placed a photographic film. The insulator material separates a plane electrode on one side, and a pointed electrode which is just in contact with the photographic film. The high voltage is applied to the pointed electrode and the other electrode is generally earthed. The photographic film can be made to rotate continuously by a clockwork mechanism. The apparatus is enclosed in a blackened box so as not to expose the photographic film. When an impulse voltage is applied to the high voltage electrode, the resultant photograph shows the growth of filamentary streamers which develop outwards from the electrode.

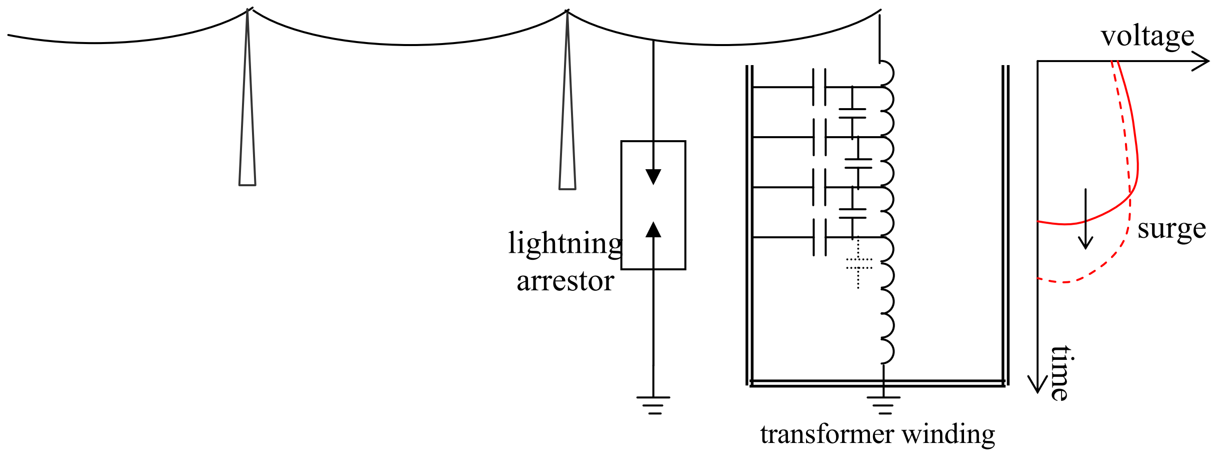
This imprint on the photographic plate is not due to normal photographic action, and occurs even through there is no visible discharge between the electrodes. If flashover of the insulator or a visible discharge occurs, then the film would become exposed and no patterns would be obtained.

These patterns obtained on the photographic film are known as Litchenberg patterns. When a positive high voltage is applied to the upper electrode, clearly defined steamers which lie almost within a definite circle is obtained. If the voltage applied is negative, then the observed pattern is blurred and the radius of the pattern is much smaller. For both types of surges, the radius of the pattern obtained increases with increase in voltage.



Litchenberg patterns

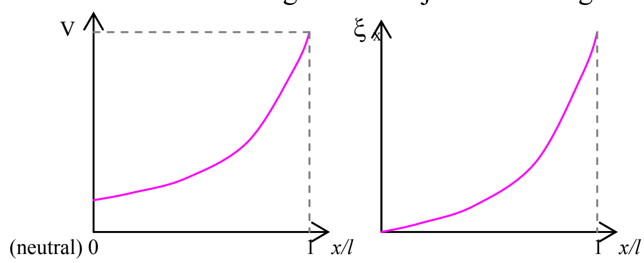
(e)



Due to the velocity of propagation of the impulse voltage would not be evenly distributed in the winding. Due to sharp rise of the voltage of the surge. there is a large difference of voltage caused in the winding as the wave front travels up the winding. Thus there would be an overvoltage across adjacent windings.

Due to the presence of the inter-winding capacitance and the capacitances-to-earth of the transformer windings, the upper elements of the transformer windings tend to be more heavily stressed than the lower portions.

Depending on the termination, there will be reflections at the far end of the winding.



If the termination is a short circuit, at the lowest point the voltage wave whose amplitude is same as the original wave but of opposite polarity is reflected. For a line which is open circuited, the reflected wave would be of the same magnitude and of the same sign.

Arising out of the reflections at the far end , there would be some coils heavily stressed.

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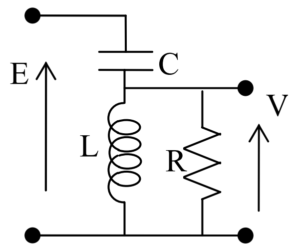
(f) The resonance principle of a series tuned **L-C** circuit can be made use of to obtain a higher voltage with a given transformer.



Let **R** represent the equivalent parallel resistance across the coil and the device under test. The current **i** would be given by

$$i = \frac{E}{\dfrac{1}{j\omega C} + \dfrac{j\omega L R}{R + j\omega L}}$$

so that $$v = i.\frac{j\omega L R}{R + j\omega L}$$

i.e. $$v = \frac{-\omega^2 L C R . E}{R + j\omega L - \omega^2 L C R} = -\frac{E . R}{j\omega L} \quad \text{at resonance}$$

Since **R** is usually very large, the **Q** factor of the circuit (Q = R/Lω) would be very large, and the output voltage would be given by

$$|v| = E.\frac{R}{L\omega} = E.Q$$

It can thus be seen that a much larger value that the input can be obtained across the device under test in the resonant principle.

This method is not suitable for power transmission, as the voltage gain occurs only at high Q and Q rapidly falls to below unity when significant power is drawn from the circuit.

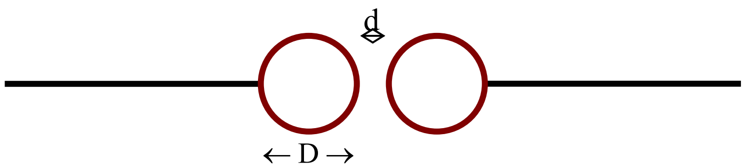
(g) The sphere gap method of measuring high voltage is reliable and is used as the standard for calibration purposes. The breakdown voltage varies with the gap spacing; and for a uniform field gap, a high consistency could be obtained.

The density of the air affects the spark-over voltage for a given gap setting.

air density correction factor $\delta = \frac{P}{760} x \frac{273+20}{273+t} = 0.386\left[\frac{P}{273+t}\right]$ under standard conditions

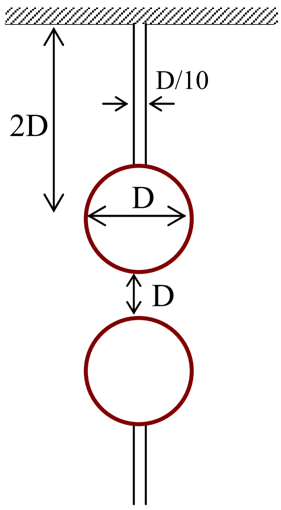
Thus the spark over voltage under the standard conditions (760 torr pressure and at 20°C) must be multiplied by the correction factor to obtain the actual spark-over voltage.

The breakdown voltage of the sphere gap is almost independent of humidity of the atmosphere, but the presence of dew on the surface lowers the breakdown voltage and hence invalidates the calibrations.



where d = gap spacing, D = sphere diameter

The breakdown voltage characteristic has been determined for similar pairs of spheres (diameters 62.5 mm, 125 mm, 250 mm, 500 mm, 1 m and 2 m)



When the gap distance is increased, the uniform field between the spheres becomes distorted, and accuracy falls. The limits of accuracy are dependant on the ratio of the spacing **d** to the sphere diameter **D**, as follows.

d	< 0.5 D,	accuracy = ± 3 %
0.75 D > d	> 0.5 D,	accuracy = ± 5 %

For accurate measurement purposes, gap distances in excess of 0.75D are not used.

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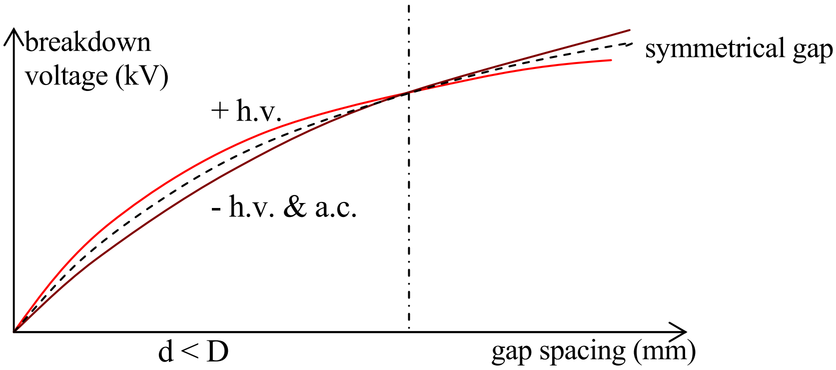


The breakdown voltage characteristic is also dependant on the polarity of the high voltage sphere in the case of asymmetrical gaps (i.e. gaps where one electrode is at high voltage and the other at a low voltage or earth potential). If both electrodes are at equal high voltage of opposite polarity (i.e. + ½ V and - ½ V), as in a symmetrical gap, then the polarity has no effect.

In sphere gaps used in measurement, to obtain high accuracy, the minimum clearance to be maintained between the spheres and the neighbouring bodies.

Peak values of voltages may be measured from 2 kV up to about 2500 kV by means of spheres.

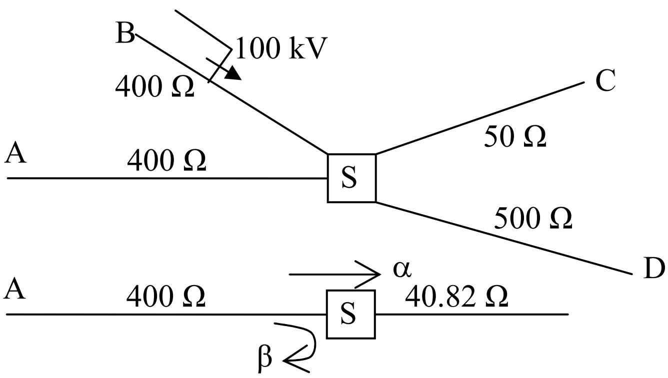
When spark gaps are to be calibrated using a standard sphere gap, the two gaps should not be connected in parallel. Equivalent spacing should be determined by comparing each gap in turn with a suitable indicating instrument.

(h) for surge arriving along BS,

SA, SB, and SC effectively appear to be in parallel

Thus effective combined Z_0

$= 400//500//50 = 40.82\ \Omega$



$\therefore\quad \alpha = \dfrac{2Z_2}{Z_1 + Z_2} = \dfrac{2 \times 40.82}{400 + 40.82} = 0.185$

and $\beta = \dfrac{Z_2 - Z_1}{Z_1 + Z_2} = \dfrac{40.82 - 400}{400 + 40.82} = -\ 0.815$

$\therefore$ surge transmitted to SD = 100 × 0.185 = 18.5 kV

and surge reflected to SB = 100 × (-0.815) = 81.5 kV

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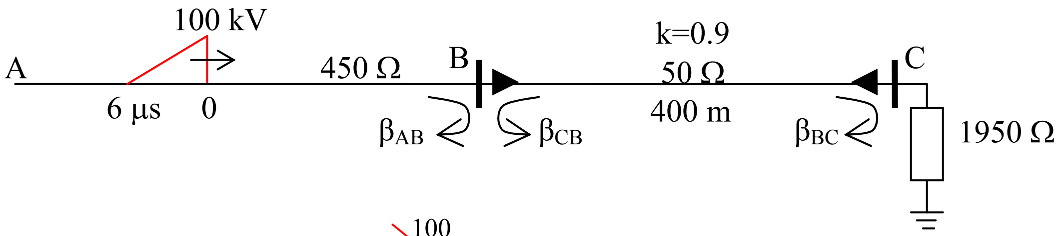
2 (a)



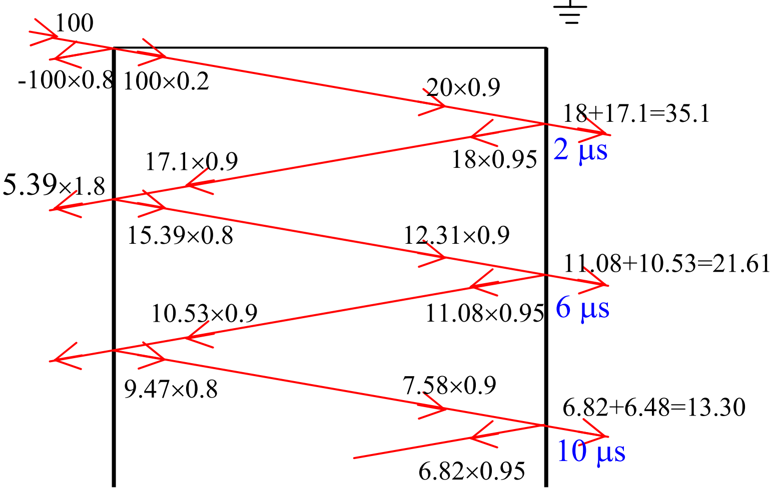
(a)

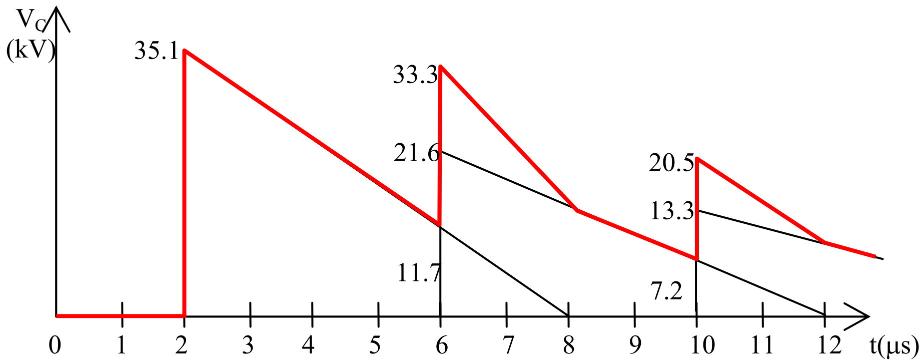
$$\beta_{AB} = \frac{50-450}{50+450} = -0.8\,,$$

$\beta_{CB} = -\,\beta_{AB} = 0.8,$

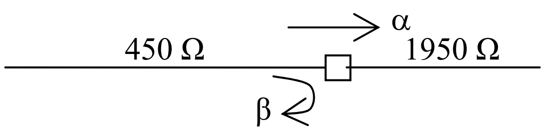
$$\beta_{BC} = \frac{1950-50}{1950+50} = 0.95\,,$$

$\tau_{BC} = 400/200 = 2\ \mu s$

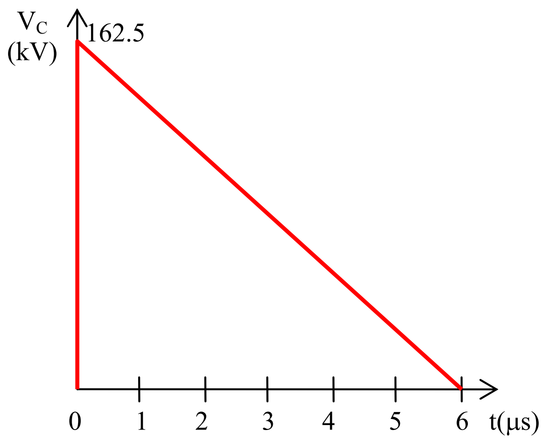




(b)



$$\alpha = \frac{2\times 1950}{450+1950} = 1.625$$



(c) Brief explanation, with appropriate calculations, the use of switching resistors in circuit breakers

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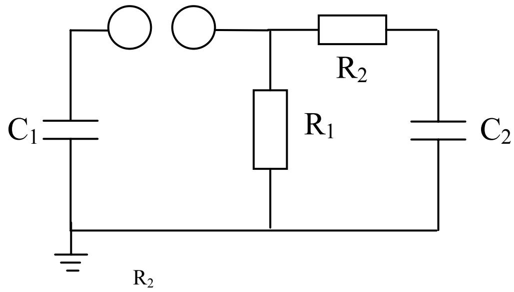
3 The impulse generator can be reduced to the form



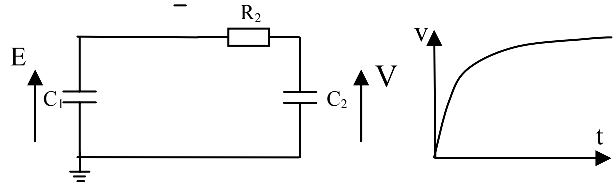
C_1 = 6 of 0.06 μF capacitors effectively in series

C_2 = 1 nF

standard waveform 1.2/50 μs

During wavefront, since $R_1 >> R_2$,

the approximate charging circuit is



giving a charging time constant

$$\frac{1}{\beta} = R_2 .(C_1//C_2) = \frac{R_2 C_1 C_2}{(C_1 + C_2)} = \eta\, R_2 C_2$$

where, voltage efficiency = $\eta = \dfrac{C_1}{C_1 + C_2}$, and $v = V_{\max}\left(1 - e^{-\beta\, t}\right)$

defining wavefront based on 30% to 90% and extrapolation

$$t_f = \frac{1}{0.90 - 0.30} \times (t_{90} - t_{30}) = \frac{1}{0.60} \times (t_{90} - t_{30}) = 1.2\,\mu\, s \;\rightarrow\; (t_{90} - t_{30}) = 0.72\ \mu s$$

$0.3\ V_m = V_m\ (1- e^{-\beta t30})$ giving $0.7 = e^{-\beta t30}$

$0.9\ V_m = V_m\ (1- e^{-\beta t90})$ giving $0.1 = e^{-\beta t90}$

therefore, $7 = e^{\beta(t90-t30)}$ giving $t_{90} - t_{30} = (\ln 7)/\beta = 0.72$

$\beta = (\ln 7)/0.72\ (\mu s)^{-1} = 2.70\ (\mu s)^{-1}$

therefore $R_2 = \dfrac{\frac{0.06}{6} + 0.001}{2.70 \times 0.01 \times 0.001} = 407.4\ \Omega$

$V_m = \eta\ E = 550$ kV

input voltage required = $550 \times \dfrac{0.01 + 0.001}{0.01}$ = 605 kV or 605/6 kV per stage

minimum rms value of input transformer secondary voltage = √2×605/6 = 142.6 kV

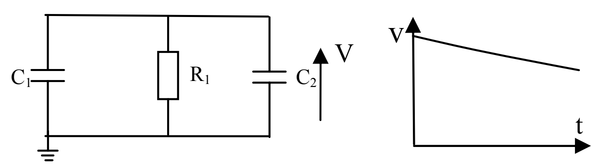
with a tolerance margin, secondary voltage required = 150 kV.

nominal energy = ½ $C_1 V_1^2$ = $\tfrac{1}{2} \times 0.01 \times 10^{-6} \times (605 \times 10^3)^2 = 1.83 \times 10^3$ J or 1.83 kJ

alternatively, energy = $\left[\tfrac{1}{2} \times 0.06 \times 10^{-6} \times \left(\dfrac{605 \times 10^3}{6} \right)^2 \times 6 \right] = 1.83$ kJ

Similarly, during wavetail, since $R_2 << R_1$,

the approximate charging circuit is



giving a discharging time constant

$1/\alpha = R_1 .(C_1+C_2) = R_1\ C_1/\eta$

and an expression $v = V_{\max} e^{-\alpha\, t}$

at wavetail $0.5\ V_m = V_m\ e^{-\alpha t}$ giving $\alpha\ t_t = \ln(2)$, $t_t = 50$ μs

therefore $\alpha = 0.693/\ t_t = 0.693/50 = 0.01386\ (\mu s)^{-1}$

i.e. R_1 = 1/(0.01+0.001)*0.01386 = 6559 Ω = 6.56 kΩ or 6 resistors or 6.56/6= 1.093 kΩ

Thus the components of the circuit are

1 wavefront control resistor = 407 Ω

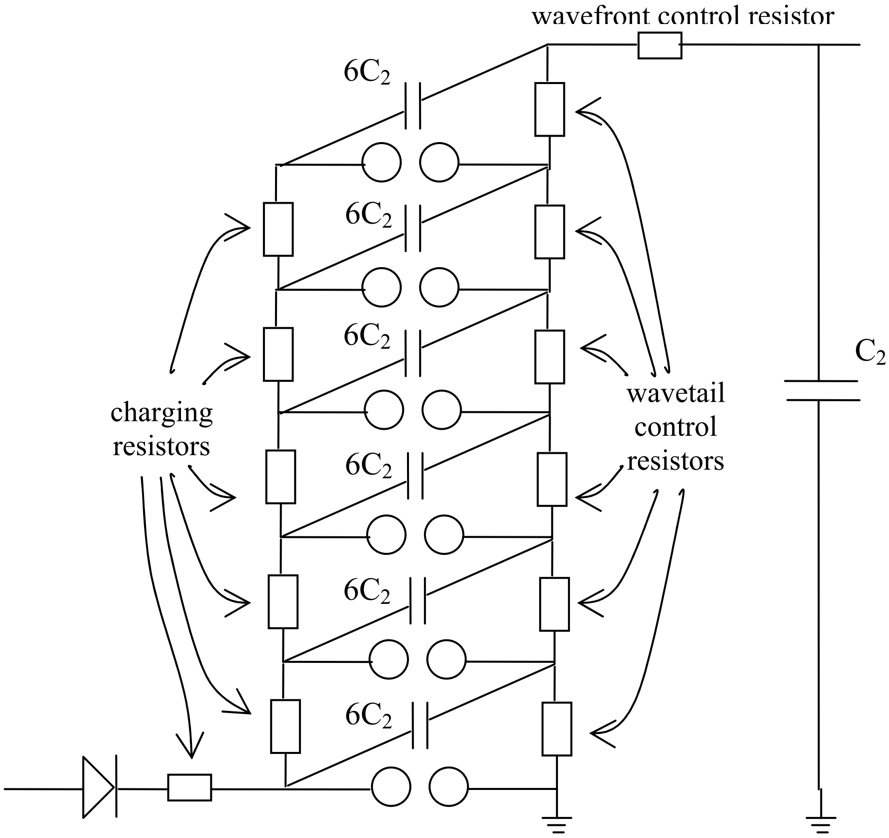
6 wavetail control resistors each of value = 1093 Ω

6 capacitors each of value ($6C_1$) = 60 nF

1 capacitor of value (C_2) = 1 nF

Select the charging resistors as about 1000 larger than the wavetail control resistors

charging resistors each of value = 1 MΩ.



4 (a) *Type tests* are done on equipment to establish that the particular design is suitable for a particular purpose . They are normally done once on new designs and when specifically requested by consumers purchasing in bulk quantities.

Ex: One minute rain test on porcelain insulators where the insulator is sprayed throughout the test with artificial rain.

Sample tests done on equipment for the purpose of verifying certain characteristics on equipment which might change during the course of manufacture. These generally involve destructive tests which cannot be done routinely.

Ex: Porosity test on porcelain insulators which needs freshly broken pieces of porcelain to show no dye penetration.

Routine tests are done on equipment for the purpose of eliminating equipment with manufacturing defects by non-destructive tests. These are generally easily verifiable.

Ex: Mechanical loading of porcelain insulators with a load 20% in excess of maximum working load of the insulator.

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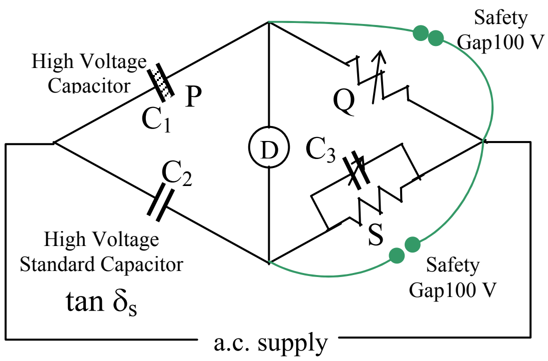
(b) In the high voltage Schering Bridge, one arm is the high voltage test capacitor (assumed to be represented by a series combination of capacitance C_1 and resistance P). The other three arms are a standard high voltage capacitor C_2 (generally a loss free air capacitor of value 100 to 500 pF) a variable low resistance Q, and a parallel combination of a standard low resistance S and a variable capacitance C_3.



The high voltage supply for the bridge is obtained through a high voltage transformer. For reasons of safety, only the high voltage test capacitor and the high voltage standard capacitor will be at high voltage. The other components are at low voltage and are not allowed to have voltages greater than about 100 V applied across them by means of safety gaps connected across them (The safety gaps are either gas discharge gaps or paper gaps). The impedance of these arms must thus necessarily be of values much less than that of the high voltage capacitors. The bridge is an unequal arm bridge, so that the relative sensitivity will be small. However, since the applied voltage is high, this is not a practical disadvantage and a reasonable variation can be obtained across the detector.

For measurements at power frequencies, the detector used is a vibration galvanometer, usually of the moving magnet type (If the moving coil type is used, it has to be tuned). The arms Q and C_3 are varied to obtain balance.

It can be shown that this bridge is frequency independent, and that at balance

$$\frac{C_2}{C_1} = \frac{Q}{S}, \quad \text{also} \quad \frac{P}{Q} = \frac{C_3}{C_2}$$

$\theta \approx \tan\theta$, $\delta_s \approx \tan\delta_s$, $\delta \approx \tan\delta$

$\delta - \delta_s = \theta$ giving $\tan\delta \approx \tan\delta_s + \tan\theta$

i.e. $\tan\delta = \tan\delta_s + \omega\, C_3\, S$

and $$C_1 = \frac{S}{Q} C_2$$

(c) r = 12mm, R = 25 mm

It can be shown that for optimum design,

Material	A	B	C
Breakdown stress ξ_{max} (kV/cm)	150	130	110
Relative Permittivity ε_r	3.5	2.5	4.4
$\xi_{max}\ \varepsilon_r$	525	325	484

$$\xi_{m1}\, r\, \varepsilon_{r1} = \xi_{m2}\, r_1\, \varepsilon_{r2} = \xi_{m3}\, r_2\, \varepsilon_{r3}$$

$r < r_1 < r_2$ so that $\xi_{m1}\, \varepsilon_{r1} > \xi_{m2}\, \varepsilon_{r2} > \xi_{m3}\, \varepsilon_{r3}$

∴ order of materials must be A, C, B starting from innermost

∴ $525 \times 12 = 484 \times r_1 = 325 \times r_2$ giving $r_1 = 13.0$ mm, $r_2 = 19.4$ mm

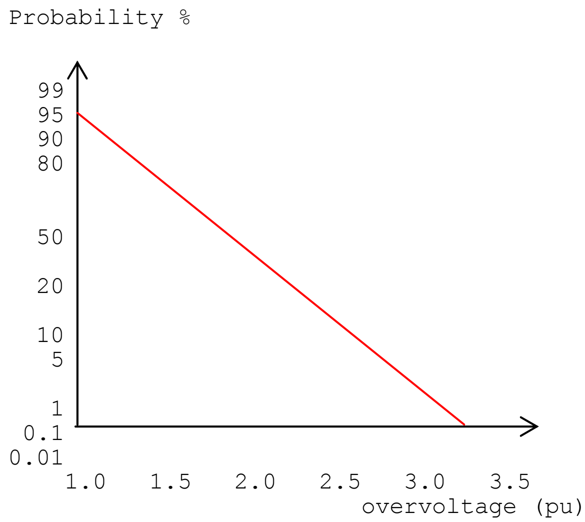
∴ thickness $t_1 = 13.0 - 12 = 1$ mm, $t_2 = 19.4 - 13.0 = 6.4$ mm, $t_3 = 15 - 19.4 = 5.6$ mm

maximum operating voltage = $\Sigma\, \xi_m\, r \ln R/r$

$$= \frac{150}{1.5} \times 1.2 \ln\frac{13.0}{12} + \frac{110}{1.5} \times 1.3 \ln\frac{19.4}{13.0} + \frac{130}{1.5} \times 1.94 \ln\frac{25}{19.4} = 90.4\,\text{kV}$$

∴ maximum r.m.s. operating voltage = $90.4/\sqrt{2} = 63.9$ kV

5 (a) In a statistical study, what has to be known is not the highest overvoltage possible, but the statistical distribution of overvoltages. The switching overvoltage probability is shown. It is seen that probability of overvoltage decreases very rapidly.

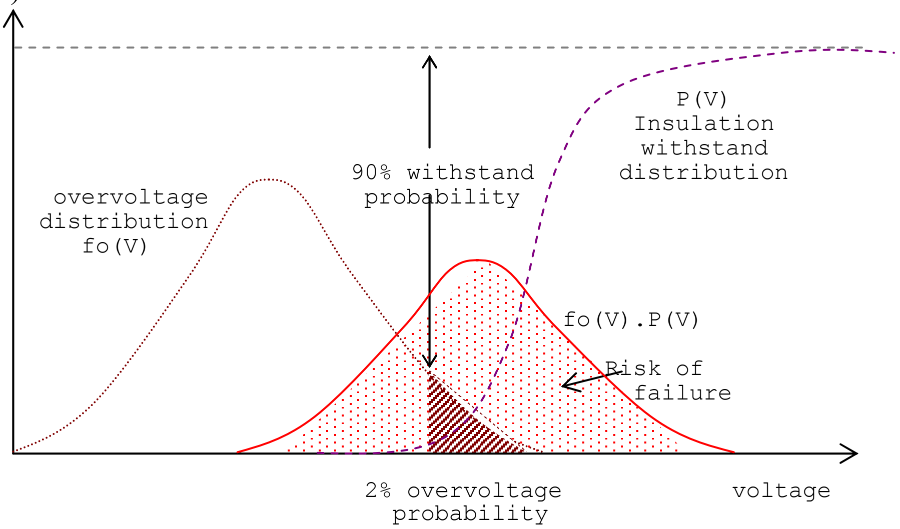


Probability of overvoltage exceeding abscissae

At the higher transmission voltages, the clearances in air do not increase linearly with voltage but approximately to $V^{1.6}$. Thus, while it may be economically feasible to protect the lower voltage lines up to a high overvoltage factor of 3.5 (say), it is not economically feasible to have such high overvoltage factors on the higher voltage lines. In the higher voltage systems, it is the switching overvoltages that is predominant and these may be controlled by proper design of switching devices or by the use of surge diverters set to operate on the higher overvoltages. In such cases, the failure probability would be extremely low.

The aim of statistical methods is to quantify the risk of failure of insulation through numerical analysis of the statistical nature of the overvoltage magnitudes and of electrical withstand strength of insulation.

The risk of failure of the insulation is dependant on the integral of the product of the overvoltage density function $f_0(V)$ and the probability of insulation failure P(V). Thus the risk of flashover per switching operation is equal to the area under the curve I $f_0(V)*P(V)*dV$.



Since we cannot find suitable insulation such that the withstand distribution does not overlap with the overvoltage distribution, in the statistical method of analysis, the insulation is selected such that the 2% overvoltage probability coincides with the 90% withstand probability as shown.

(b) When a surge voltage wave traveling on an overhead line causes an electric field around it exceeding the critical stress of air, corona will be formed. This extracts energy from the surge and waveform distortion occurs.

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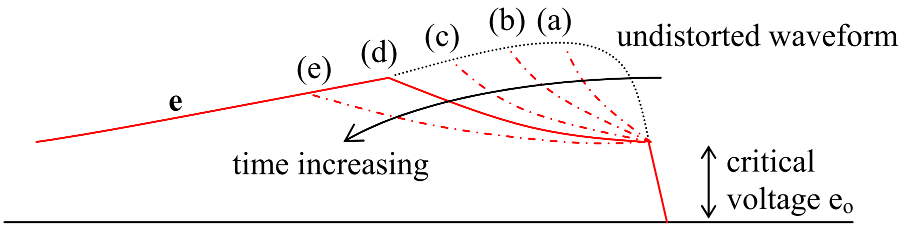


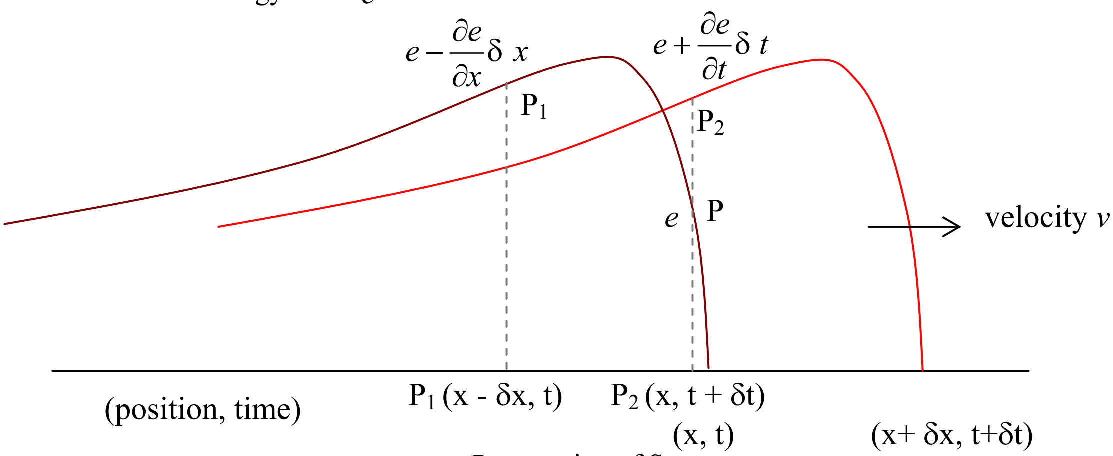
Corona thus reduces the steepness of the wavefront above the critical voltage, as the surge travels down the line.

Energy associated with a surge waveform = $\frac{1}{2} C\, e^2 + \frac{1}{2} L\, i^2$

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

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

So that the total wave energy $= C\, e^2$



Propagation of Surge

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

Then voltage at point P_1 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+Δt , when the surge at P_1 moves forward to P_2.

[Note: $\frac{\partial e}{\partial x}, \frac{\partial e}{\partial t}$ would in fact be negative quantities on the wavefront.]

Thus corona causes a depression in the voltage from $(e - v\frac{\partial e}{\partial x}\delta t)$ to $(e + \frac{\partial e}{\partial t}\delta t)$, with a corresponding loss of energy of $C\left|(e - v\frac{\partial e}{\partial x}\delta t)^2 - (e + \frac{\partial e}{\partial t}\delta t)^2\right|$ 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 the voltage from e to $(e + \frac{\partial e}{\partial t}\delta t)$ is given by

$k\left|(e + \frac{\partial e}{\partial t}\delta t - e_0)^2 - (e - e_0)^2\right|$ 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 $v\frac{\partial e}{\partial x} = -\left[1 + \frac{k}{C}.\frac{(e - e_0)}{e}\right]\frac{\partial e}{\partial t}$

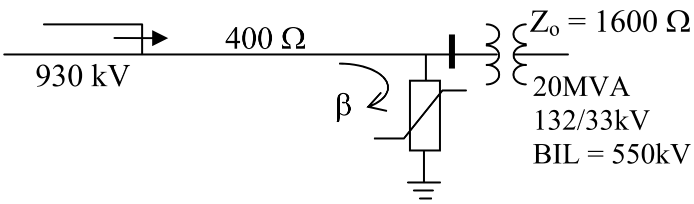
Wave propagation under ideal conditions is written in the form $v\frac{\partial e}{\partial x} = -\frac{\partial e}{\partial t}$

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

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

$$t = \frac{x}{v_e} = \frac{x}{v}\left[1+\frac{k}{C}\left[\frac{e-e_o}{e}\right]\right], \ i.e. \ \left[\frac{x}{v_e}-\frac{x}{v}\right] = \frac{x}{v}.\frac{k}{C}\left[\frac{e-e_o}{e}\right]$$

$\left(\dfrac{x}{v_e} - \dfrac{x}{v}\right)$ is the time lag Δt corresponding to the voltage element at **e**. Thus $\dfrac{\Delta t}{x} = \dfrac{k}{v.C}\left[1 - \dfrac{e_0}{e}\right]$



(c) $\beta = \dfrac{1600-400}{1600+400} = 0.6$, α = 1.6

open circuit voltage across arrestor

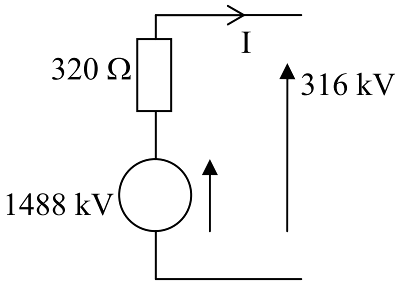
= 1.6 × 930 = 1488 kV

equivalent Thevenin's impedance across arrestor

= 400//1600 = 320 Ω

consider the 5 kA arrestor, discharge voltage = 316 kV

$$I = \frac{1488-316}{320} = 3.66\,\text{kA} < 5\,\text{kA}$$



chosen current rating is satisfactory.

316 kV < 550 kV, so that the discharge voltage is acceptable.

Thus the chosen arrestor is satisfactory.

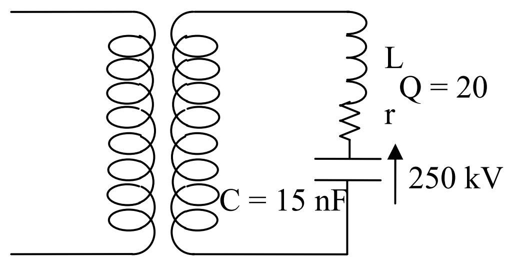
6 (a)

$$x_t = 0.08 \times \frac{(50\times10^3)^2}{100\times10^3} = 2000\,\Omega$$

$$r_t = 0.02 \times \frac{(50\times10^3)^2}{100\times10^3} = 500\,\Omega$$

$$x_C = \frac{1}{15\times10^{-9}\times100\pi} = 212{,}207\,\Omega$$

$$x_L = 100\pi \times L, \ \ r = \frac{x_L}{20} = 5\pi \times L$$



100 kVA, 230V/50 kV, 50 Hz

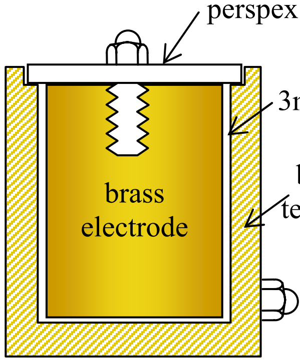
x_t = 8%, r_t = 2%

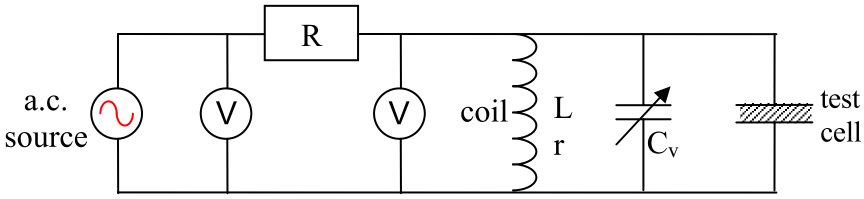
at resonance, 100πL + 2000 = 212,207 giving L = 669 H, r = 202,207/20 = 10.11 kΩ

from potential divider action, $\dfrac{250\times10^3}{V_s} = \dfrac{212{,}207}{500+10{,}110}$ giving V_s = 12,500 V

∴ primary voltage V_p = 12,500 × 230/50×10^3 = 57.5 V

(b) The test cell used in the measurement consists of a brass cell inside which is suspended a brass electrode from a perspex cover. The outer cell is the earthed electrode, and there is a gap of 3 mm all round between this and the inner brass electrode. Since the electrodes are near each other, the stray capacitance must be considered.





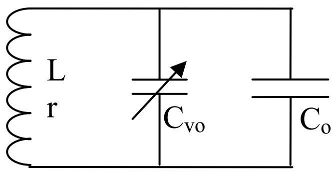
The test cell is connected in parallel with a variable capacitor and made part of a resonant circuit. In the circuit, R is a high series resistance used to keep the total current in the circuit very nearly constant.

If C_v is the value of the variable capacitor at resonance, at the angular frequency ω,

then $\omega^2 L(C_v + C_{test}) = 1$

The stray capacitance can be eliminated using the following procedure at the selected frequency (say 1 MHz). For resonance, $C_v + C_{test}$ must be a constant.

(i) With the outer cell and with only the brass screw and the perspex cover of the inner cell in position, the variable capacitor C_{v0} is varied until resonance is obtained. Under this condition, only the stray capacitance C_0 is present, and the total capacitance will be at resonance with the coil inductance L. The effective capacitance, in this case, is $C_{v0} + C_0$.



The Q-factor of the circuit will be dependant on the resistance r of the coil. The Q-factor can be determined from the half-power points. The variable capacitance is varied in either direction from resonance until the half-power points (voltage corresponding to 1/√2) are reached. If C_+ and C_- are the values at the half power points, then it can be shown that the Q factor is given by

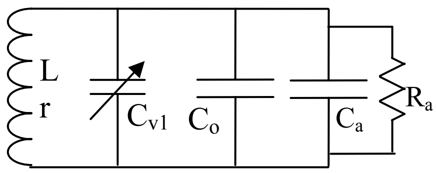
$$Q = \frac{C_+ + C_-}{C_+ - C_-} = \frac{2C + (\Delta C_+ - \Delta C_-)}{\Delta C_+ + \Delta C_-}$$

where ΔC_+, ΔC_- are the variations at the half-power points

If Q is high, $\Delta C_+ = \Delta C_- = \Delta C$, so that $Q = \dfrac{C}{\Delta C}$

(ii) The inner electrode is now screwed in, and the circuit is again adjusted for resonance at the same frequency.

If C_a is the capacitance of the active portion of the test cell with air as dielectric, and R_a is the equivalent shunt resistance of the circuit with air as dielectric, then the total value of the capacitance required must remain the same. This is true for all cases.



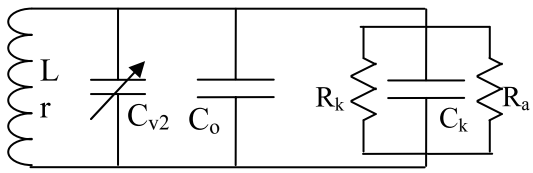
Thus we have

$$C_{v0} + C_0 = C_{v1} + C_0 + C_a$$
$$\therefore C_a = C_{v0} - C_{v1}$$

The Q-factor of the circuit however will be different from the earlier value, due to the additional parallel resistance. If the parallel equivalent resistance of the inductor is considered, then it is seen that the overall Q factor Q_a is given as the parallel equivalent of the Q-factors of the coil resistance and the resistance R_a. The Q-factor corresponding to the resistance R_a is ωCR_a, so that $\frac{1}{Q_a} = \frac{1}{Q_L} + \frac{1}{\omega C R_a}$

(iii) The liquid is now introduced into the test cell.

[The liquid level should be slightly below the perspex cover, so that the surface condition of the perspex is not changed.]



If R_k is the equivalent shunt resistance of the liquid, and k is the relative permittivity of the liquid dielectric, then the capacitance of the active portion of the test cell with the liquid would be kC_a.

If C_{v2} is the value of the variable capacitor at resonance, then

$$C_{v0} + C_0 = C_{v2} + C_0 + k\,C_a \quad \text{giving} \quad k\,C_a = C_{v0} - C_{v2} \quad \therefore\ k = \frac{C_{v0} - C_{v2}}{C_{v0} - C_{v1}}$$

Also we have the equivalent Q factor Q_k equivalent to the parallel equivalent. Thus

$$\frac{1}{Q_k} = \frac{1}{Q_L} + \frac{1}{\omega C R_a} + \frac{1}{\omega C R_k}$$

Thus the inverse of ωCR_k can be determined from

$$\frac{1}{\omega C R_k} = \frac{1}{Q_k} - \frac{1}{Q_a}, \qquad \frac{1}{Q_k}, \frac{1}{Q_a} \text{ can be calculated using } \frac{1}{Q_k} = \frac{(\Delta C)_k}{C}, \ \frac{1}{Q_a} = \frac{(\Delta C)_a}{C}$$

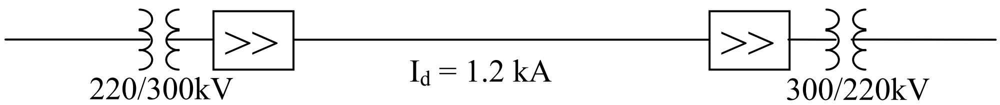
The loss factor of the dielectric is given by

$$\text{loss factor} = \frac{1}{\omega C_k R_k} = \frac{1}{\omega C R_k}.\frac{C}{C_k} = \frac{C}{k C_a}.\left[\frac{1}{Q_k} - \frac{1}{Q_a}\right] = \frac{C}{k C_a}.\frac{[\Delta C_k - \Delta C_a]}{C} = \frac{1}{k C_a}.[\Delta C_k - \Delta C_a]$$

$$\text{i.e. loss factor} = \frac{\Delta C_k - \Delta C_a}{C_{v0} - C_{v2}}$$

In making connections it is essential that care is taken to minimise stray capacitances by using short leads, and the components should not be disturbed during the experiment.

7 (a)



For the 6-valve bridge, with zero firing delay, the voltage waveforms across the thyristors are shown. At any given instant, one thyristor valve on either side is conducting.

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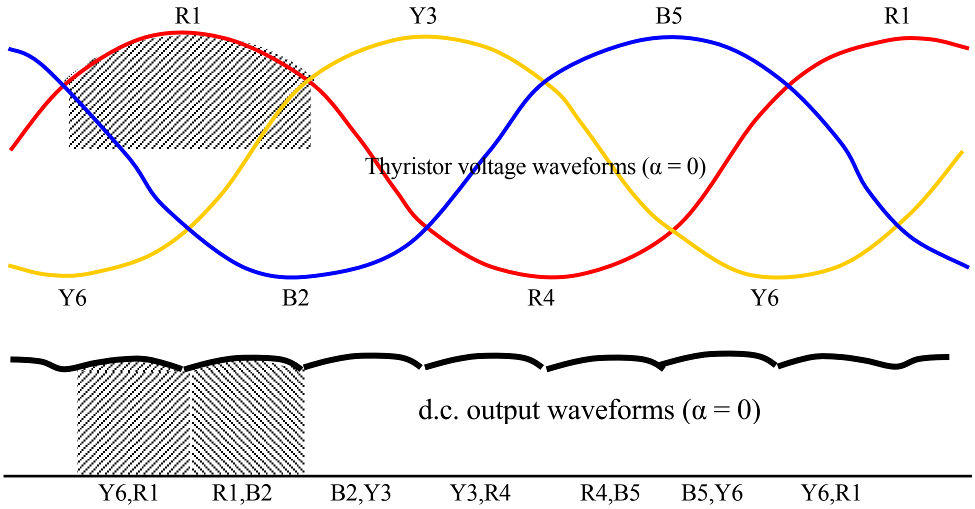

The corresponding d.c. output voltage waveforms are shown in figure 11.4.

If E is the r.m.s. line-to-line voltage, if $\alpha = 0$, $\gamma = 0$, then the direct voltage output is given by

$$V_{do} = 2\,x\,\frac{E}{\sqrt{3}}\,x\,\sqrt{2}\,x\,\frac{3}{2\pi}\int_{-\frac{\pi}{3}}^{\frac{\pi}{3}}\cos\theta\;d\theta = E\,.\,\frac{3\sqrt{2}}{\pi}\,.\,\frac{1}{\sqrt{3}}\left[\,2\,x\sin\frac{\pi}{3}\,\right]$$

$$V_{do} = \frac{3\sqrt{2}}{\pi}\,.\,E = 1.350\,E \quad = 1.350 \times 300 = 405 \text{ kV}$$

Nominal voltage of link = 405 kV.

(b) $V_d = V_0 \cos w + \frac{3\,\omega\,L_c}{\pi} I_d$ for rectification and $V_d = V_0 \cos\delta - \frac{3\,\omega\,L_c}{\pi} I_d$ for inversion

$\delta = 12^o$, I_d =1.2 kA so that $V_d = 405\cos 12^o - \frac{3\times 20}{\pi}\times 1.2 = 391.26 - 22.92 = 368.3\,\text{kV}$

(c) Power delivered = $V_d\ I_d$ = 368.3 × 1.2 = 442 MW

(d) $V_d = V_0 \cos\beta + \frac{3\,\omega\,L_c}{\pi} I_d$ so that 368.3 = 405 cos β + 22.92 giving cos β = 0.853, β = 31.48°

$\beta = \gamma + \delta$ giving commutation angle $\gamma = \beta - \delta$ = 31.48 – 12 = 19.5°

(e) The power factor associated with the convertor on the a.c. side can be calculated as follows.

Active power supplied to d.c. link = $V_d\ I_d$

Active power supplied from a.c. system = √3 E I cos φ

Since the convertor does not consume any active power, there must be power balance.

$V_d\ I_d$ = √3 E I cos φ

From this the power factor can be calculated as follows.

$$\cos\phi = \frac{V_d\,I_d}{\sqrt{3}\,E\,I} \quad \text{giving} \quad \cos\phi = \frac{\frac{1}{2}V_0(\cos\alpha + \cos w)\,\frac{\pi}{\sqrt{6}}\,I}{\sqrt{3}\,\frac{\pi}{3\sqrt{2}}\,V_0\,I}$$

cos ϕ = ½ (cos α + cos w) for rectifier or ½ (cos δ + cos β) for invertor

cos ϕ = ½ (cos 12° + cos 31.48°) = 0.915

(f) fundamental component of current on a.c. side is obtained from

P = √3 E I cos ϕ,

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so that $442 = \sqrt{3} \times 300 \times I \times 0.915$ giving $I = 0.93$ kA (secondary)
or $442 = \sqrt{3} \times 220 \times I \times 0.915$ giving $I = 1.27$ kA (primary)