

Internal Test3 –November 2019

Sub:	High Voltage Engineering						Code:	15EE73	
Date:	16/11 /2019	Duration:	90 mins	Max Marks:	50	Sem:	VII	Branch:	EEE
Note: Answer any <b>FIVE</b> full questions with neat diagram wherever necessary.									

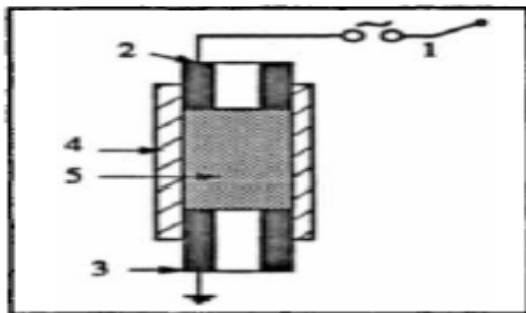
		Marks	OBE	
			CO	RB T
1.	Explain with suitable figures the principles and functioning of (a) expulsion gaps, (b) protector tubes.	[5+5]	CO5	L2
2.	What are the mechanisms by which lightning strokes develop and induce overvoltages on overhead power lines?	[10]	CO5	L2
3.	What are partial discharges? How are they detected using blance detection?	[2+8]	CO6	L2
4.	What are the causes for switching and power frequency overvoltages? How are they controlled in power systems?	[5+5]	CO5	L2
5.	What is a surge diverter? Explain its function as a shunt protective device with a neat diagram.	[3+7]	CO6	L2
6a.	A resistance divider of 1400 kV (impulse) has a high voltage arm of 16 kilohms and a low voltage arm consisting 16 members of 250 ohms, 2 watt resistors in parallel. The divider is connected to a CRO through a cable of surge impedance 75 ohms and is terminated at the other end through a 75 ohm resistor. Calculate the exact divider ratio.	[5]	CO4	L3
6b.	A transmission line of surge impedance 500Ω is connected to a cable of surge impedance 60 Ω at the other end. If a surge of 500 kV travels along the line to the junction point, find the voltage build-up at the junction ?	[5]	CO5	L3
7.	Write short notes on: a) RC Mixed Potential Divider, b) Impulse current Generator	[6+4]	CO4	L3

### 1a) Protective Devices

In regions where lightning strokes are intensive or heavy, the overhead lines within these zones are fitted with shunt protected devices.

On the line itself two devices known as expulsion gaps and protector tubes are used. **Expulsion gaps** Expulsion gap is a device which consists of a spark gap together with an arc quenching device which extinguishes the current arc when the gaps breakover due to overvoltages. A typical such arrangement is shown in Fig.

This essentially consists of a rod gap in air in series with a second gap enclosed within a fibre tube. In the event of an overvoltage, both the spark gaps breakdown simultaneously. The current due to the overvoltage is limited only by the tower footing resistance and the surge impedance of the ground wires. The internal arc in the fibre tube due to lightning current vapourizes a small portion of the fibre material. The gas thus produced, being a mixture of water vapour and the decomposed fibre product, drive away the arc products and ionized air. When the follow-on power frequency current passes through zero value, the arc is extinguished and the path becomes open circuited. Meanwhile the insulation recovers its dielectric strength, and the normal conditions are established. The lightning and follow-up power frequency currents together can last for 2 to 3 half cycles only. Therefore, generally no disturbance in the network is produced. For 132 or 220 kV lines, the maximum current rating may be about 7,500 A.



1. External series gap
2. Upper electrode
3. Ground electrode
4. Fibre tube
5. Hollow space

**Fig. 8.20a** Expulsion gap

### b) Protector tubes

A protector tube is similar to the expulsion gap in, construction and principle.

It also consists of a rod or spark gap in air formed by the line conductor and its high voltage terminal. It is mounted underneath the line conductor on a tower.

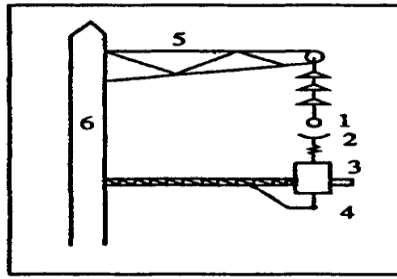
The arrangement is shown in Fig.

The hollow gap in the expulsion tube is replaced by a nonlinear element which offers a very high impedance at low currents but has low impedance for high or lightning currents. When an overvoltage occurs and the spark gap breakdown, the current is limited both by its own resistance and the tower footing resistance. The overvoltage on the line is reduced to the voltage drop across the protector tube.

After the surge current is diverted and discharged to the ground, the follow-on normal power frequency current will be limited by its high resistance.

After the current zero of power frequency, the spark gap recovers the insulation strength quickly.

Usually, the flashover voltage of the protector tube is less than that of the line insulation, and hence it can discharge the lightning overvoltage effectively.



1. Line conductor on string insulator
2. Series gap
3. Protector tube
4. Ground connection
5. Cross arm
6. Tower body

Fig. 8.20b Protector tube mounting

## 2. Mechanism of Lightning Strokes

When the electric field intensity at some point in the charge concentrated cloud exceeds the breakdown value of the moist ionized air ( $= 10 \text{ kV/cm}$ ), **an electric streamer with plasma** starts towards the ground with a **velocity of about 1/10 times** that of the light, but may progress only about 50 m or so before it comes to a halt emitting a bright flash of light. The halt may be due to insufficient build-up of electric charge at its head and not sufficient to maintain the necessary field gradient for further progress of the streamer. But after a short interval of about  $100 \mu\text{s}$ , the streamer again starts out repeating its performance. The total time required for such a stepped leader to reach the ground may be 20 ms. The path may be quite lustrous, depending on the local conditions in air as well as the electric field gradients. Branches from the initial leader may also be formed. Since the progress of this leader stroke is by a series of jumps, it is referred as stepped leader.

The lightning stroke and the electrical discharges due to lightning are explained based on the **"streamer" or "kanel" theory for spark discharges in long gaps with non-uniform electric fields**.

The lightning consists of few separate discharges starting from a leader discharge and culminates in return strokes or main discharges.

After the leader touches the ground, the return stroke follows. As the leader moves towards the ground, positive charge is directly accumulated under the head of the stroke or canal. By the time the stroke reaches the ground or comes sufficiently near the ground, the electrical field intensity on the ground side is sufficiently large to build up the path.

Hence, the positive charge returns to the cloud neutralizing the negative charge, and hence a heavy current flows through the path. The velocity of the return or main stroke ranges from 0.05 to 0.5 times the velocity of light, and currents will be of the order of 1000 to 250,000 A.

The return strokes vanish before they reached the cloud, suggesting that the charge involved is that conferred to the stroke itself.

After the completion of the return stroke, a much smaller current of 100 to 1000 A may continue to flow which persists approximately 20 ms. Due to these currents the initial breakdown points in the cloud are considerably reduced and discharges concentrate towards this point. Therefore, additional reservoirs of charge become available due to penetration of a cloud mass known as preferred paths and lead to repeated strokes. The leader strokes of the repeated strokes progress with much less velocity ( $\ll 1\%$  of that of light) and do not branch. This stroke is called continuous leader, and return stroke for this leader follows with much less current. The interval between the repeated strokes may be from 0.6 ms to 500 ms with an average of 30 ms. Multiple strokes may last for 1 s. The total duration of the lightning may be more than 1 s.

The current from the ground by the main return stroke may have a peak value of 250,000 A and rates of rise may be as high as  $100 \text{ kA}/\mu\text{s}$  or  $10^{11} \text{ A/s}$ .

Important parameters : the time intervals between successive strokes, the number of successive strokes, the duration of lightning discharges the discharge current, the rate of rise of current, and wavefront and wave tail times and their probability distribution

3. It was observed that the dissipation factor ( $\tan \delta$ ) was voltage dependent and hence became a criterion for the monitoring of the high voltage insulation weak points in an insulation like voids, cracks, and other imperfections lead to internal or intermittent discharges in the insulation.

- These imperfections being small were not revealed in capacitance measurements but were revealed as power loss components in contributing for an increase in the dissipation factor.
- In modern terminology these are designated as "**partial discharges**" which in course of time reduce the strength of insulation leading to a total or **partial failure or breakdown of the insulation**.

• **Balanced Detection Method**

- In the straight detection method, the external disturbances are not fully rejected.
- The filter used to block the noise sources may not be effective.
- The Schering bridge employed for the  $\tan \delta$  measurement is sometimes used.
- In this method, the test object is not grounded.
- A **modification** to the Schering bridge detector is **the differential discharge detector**, given by Kreuger.
- Both the schemes are given in Fig. 9.23.
- The bridges are tuned and balanced at 50 Hz.
- A filter is used across the detector terminals to block the 50 Hz components present
- Signals in the range from 5 to 50 kHz are allowed to pass through the filter and amplified.
- The CRO gives the display of the pulse pattern.
- Any external interference from outside is balanced out, and only internally (test piece) generated pulses are detected.
- In the modified scheme, another test sample called dummy sample is used in the place of the standard condenser.
- The capacitance and  $\tan \delta$  of the dummy sample are made approximately equal, but need not be equal.
- **The disadvantage is that if two discharges occur in both the samples simultaneously, they cancel out, but this is very rare.**
- The main advantage of the second method is its capacity for better rejection of external noise and use of the wide frequency band with better resolution of the individual pulses.

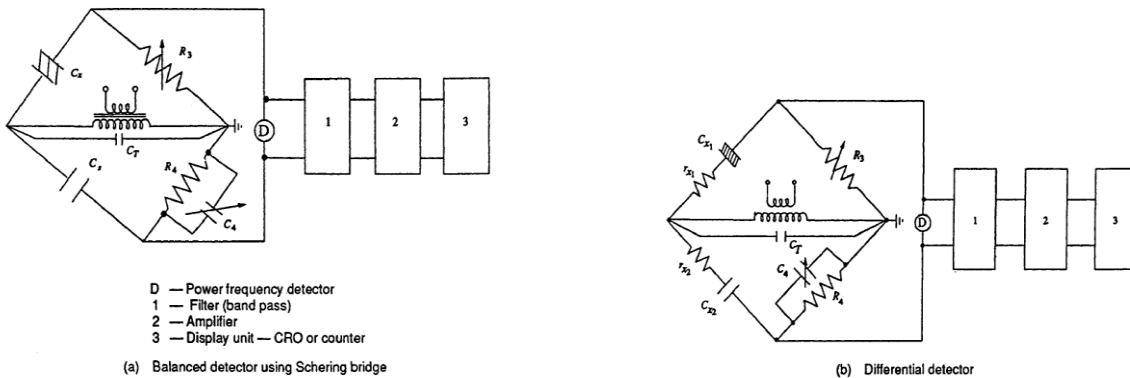


Fig. 9.23 Balanced discharge detector schemes

4. The making and breaking of electric circuits with switchgear may result in abnormal over voltages in power systems having large inductances and capacitances.

- Overvoltages are generated in EHV systems when there is a sudden release of internal energy stored either in the electrostatic form (in the capacitance) or in the electromagnetic form (in the inductance).
- The different situations under which this happens are summarised as

(i) interruption of low inductive currents (current chopping) by high speed circuit breakers. This occurs when the transformers or reactors are switched Off

(ii) interruption of small capacitive currents, such as switching off of unloaded lines etc.

(iii) *ferro-resonance condition*

This may occur when poles of a circuit breaker do not close simultaneously

(iv) energization of long EHV or UHV lines.

The other situations of switching that give rise to switching overvoltages of shorter duration (0.5 to 5 ms) and lower magnitudes (2.0 to 2.5 p.u.) are

a) single pole closing of circuit breaker

(b) interruption of fault current when the L-G or L-L fault is cleared

(c) resistance switching used in circuit breakers

(d) switching lines terminated by transformers

(e) series capacitor compensated lines

(f) sparking of the surge diverter located at the receiving end of the line to limit the lightning overvoltages

- The measures taken to control or reduce the overvoltages are
  - (i) one step or multi-step energization of lines by pre\_insertion of resistors,
  - (ii) phase controlled closing of circuit breakers with proper sensors,
  - (iii) drainage of trapped charges on long lines before the reclosing of the lines, and
  - (iv) limiting the over voltages by using surge diverters.

### Power Frequency Overvoltages in Power Systems

The main causes for power frequency and its harmonic overvoltages are

(a) sudden loss of loads,

(b) disconnection of inductive loads or connection of capacitive loads,

(c) Ferranti effect, unsymmetrical faults, and

(d) saturation in transformers, etc.

Overvoltages of power frequency harmonics and voltages with frequencies nearer to the operating frequency are caused during tap changing operations, by magnetic or ferro-resonance phenomenon in large power transformers, and by resonating overvoltages due to series capacitors with shunt reactors or transformers.

The duration of these overvoltages may be from one to two cycles to a few seconds depending on the overvoltage protection employed.

#### (a) Sudden Load Rejection

Sudden load rejection on large power systems causes the **speeding up of generator prime movers**. The **speed governors** and **automatic voltage regulators** will intervene to restore normal conditions. But **initially** both the **frequency** and **voltage increase**.

The approximate voltage rise, neglecting losses, etc. may be taken as

$$v = \frac{f}{f_0} E' \left[ \left( 1 - \frac{f}{f_0} \right) \frac{x_s}{x_c} \right]$$

where  $x_s$  is the reactance of the generator (« the sum of the transient reactances of the generator and the transformer),  $x_c$  is the capacitive reactance of the line at open end at increased frequency,  $E'$  the voltage generated before the over-speeding and load rejection,  $f$  is the instantaneous increased frequency, and  $f_0$  is the normal frequency

#### (b) Ferranti Effect

Long uncompensated transmission lines exhibit voltage rise at the receiving end. The voltage rise at the receiving end  $V_2$  is approximately given by

where,  $V_1$  = sending end voltage,

$l$  = length of the line,

$\beta$  = phase constant of the line

$$V_2 = \frac{V_1}{\cos \beta l}$$

$$\approx \left[ \frac{(R + j\omega L)(G + j\omega C)}{LC} \right]^{1/2}$$

$\approx$  about  $6^\circ$  per 100 km line at 50 Hz frequency.

$\omega$  = angular frequency for a line

$R$  — Resistance per unit length

$C$  — Capacitance per unit length

$L$  — Inductance per unit length

$G$  — Leakage conductance per unit length

Considering that the line capacitance is concentrated at the middle of the line, under open circuit conditions at the receiving end, the line charging current

$$I_C \approx j\omega CV_1 = \frac{V_1}{X_C} \quad \text{and the voltage } V_2 \approx V_1 \left[ 1 - \frac{X_L}{2X_C} \right] \quad \text{where,} \quad \begin{array}{l} X_L = \text{line inductive reactance, and} \\ X_C = \text{line capacitive reactance.} \end{array}$$

### (c) Ground Faults and Their Effects

Single line to ground faults cause rise in voltages in other healthy phases. Usually, with solidly grounded systems, the increases in voltage (phase to ground value) will be less than the line-to-line voltage. With effectively grounded systems, i.e. with

$$\frac{X_0}{X_1} \leq 3.0 \text{ and } \frac{R_0}{X_1} \leq 1.0$$

(where,  $R_0$  and  $X_0$  are zero sequence resistance and reactance and  $X_1$  is the positive sequence reactance of the system), the rise in voltage of the healthy phases does not usually exceed 1.4 per unit.

### (d) Saturation Effects

- When voltages above the rated value are applied to transformers, their magnetizing currents (no load currents also) increase rapidly and may be about the full rated current for 50% overvoltage.
- These magnetizing currents are not sinusoidal in nature but are of a peaky waveform.
- The third, fifth, and seventh harmonic contents may be 65%, 35%, and 25% of the exciting current of the fundamental frequency corresponding to an overvoltage of 1.2 p.u.
- For third and its multiple harmonics, zero sequence impedance values are effective, and delta connected windings suppress them.
- But the shunt connected capacitors and line capacitances can form resonant circuits and cause high third harmonic overvoltages.
- When such overvoltages are added, the voltage rise in the lines may be significant. For higher harmonics a series resonance between the transformer inductance and the line capacitance can occur which may produce even higher voltages.

### Control of Overvoltages Due to Switching

The overvoltages due to switching and power frequency may be controlled by

- energization of transmission lines in one or more steps by inserting resistances and withdrawing them afterwards,
- phase controlled closing of circuit breakers,
- drainage of trapped charges before reclosing,
- use of shunt reactors, and
- limiting switching surges by suitable surge diverters

#### (a) Insertion of Resistors

- It is normal and a common practice to insert resistances in series with circuit breaker contacts when switching on but short circuiting them after a few cycles.
- This will reduce the transients occurring due to switching.
- The voltage step applied is first reduced to  $Z_0(R + Z_0)$  per unit where  $Z_0$  is the surge impedance of the line.

- It is reflected from the far end unchanged and again reflected back from the near end with reflection factor  $(R - Z_0)/(R + Z_0)$  per unit.

If  $R = Z_0$ , there is no reflection from the far end.

### (b) Phase Controlled Switching

Overvoltages can be avoided by controlling the exact instances of the closing of the three phases separately. But this necessitates the use of complicated controlling equipment and therefore is not adopted.

### (c) Drainage of Trapped Charge

When lines are suddenly switching off, "electric charge" may be left on capacitors and line conductors. This charge will normally leak through the leakage path of the insulators, etc.

Conventional potential transformers (magnetic) may also help the drainage of the charge.

An effective way to reduce the trapped charges during the lead time before reclosing is by temporary insertion of resistors to ground or in series with shunt reactors and removing before the closure of the switches.

### (d) Shunt Resistors

Normally all EHV lines will have shunt reactors to limit the voltage rise due to the Ferranti effect.

They also help in reducing surges caused due to sudden energizing.

However, shunt reactors cannot drain the trapped charge but will give rise to oscillations with the capacitance of the system.

Since the compensation given by the reactors will be less than 100%, the frequency of oscillation will be less than the power frequency and overvoltages produced may be as high as 1.2 p.u.

Resistors in series with these reactors will suppress the oscillations and limit the over voltages.

Limiting the switching and power frequency over voltages by using surge diverters.

## 5. Surge Diverters

These are non-linear resistors in series with spark gaps which act as fast switches. A

typical surge diverter or lightning arrester is shown in Fig. 8.23 and its characteristics are given in Fig. A number of non-linear resistor elements made of silicon carbide are stacked one over the other into two or three sections. They are usually separated by spark gaps (see Fig. 8.23). the entire assembly is housed in a porcelain water-tight housing. The volt-ampere characteristic of a resistance element is of the form

$$I = kV^a \quad \text{where, } I = \text{discharge current,}$$

$V = \text{applied voltage across the element, and}$

$k$  and  $a$  are constants depending on the material and dimensions of the element

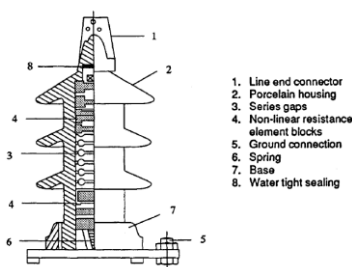


Fig. 8.23 Non-linear element surge diverter

When a surge voltage is applied to the surge diverter, it breaks

down giving the discharge current  $i_d$  and maintains a voltage  $V_d$  across it. Thus, it provides a protection to the apparatus to be protected above the protective level  $V_p$ .

The lighter designs operate for smaller duration of currents, while the heavy *duty* surge diverters with assisted or active gaps are designed for high currents and long duration surges.

The lighter design arresters can interrupt 100 to 300 A of power frequency follow-on current and about 5000 A of surge currents.

If the current is to be more and has to be exceeded, the number of series elements has to be increased or some other method to limit the current has to be used. In heavy duty arresters, the gaps are so arranged that the arc burns in the magnetic field of the coils excited by power frequency follow-on currents.

During lightning discharges, a high voltage is induced in the coil by the steep front of the surge, and sparking occurs in an auxiliary gap.

For power frequency follow-on currents, the auxiliary gap is extinguished, as sufficient voltage will not be present across the auxiliary gap to maintain an arc. The main gap arcs occur in the magnetic field of the coils. The magnetic field, aided by the born shaped main gap electrodes, elongates the arc and quenches it rapidly. The follow-on current is limited by the voltage drop across the arc and the resistance element. During surge discharge the lightning protective level becomes low.

Sometimes, it is possible to limit the power frequency and other overvoltages after a certain number of cycles using surge diverters. The permissible voltage and duration depend on the thermal capacity of the diverter. The rated diverter voltage is normally chosen so that it is not less than the power frequency overvoltage expected (line to ground) at the point of installation, under any faulty or abnormal operating condition.

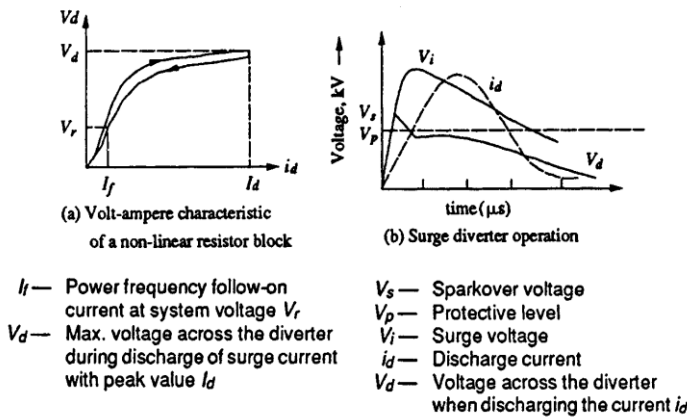


Fig. 8.24 Characteristics of a surge diverter

### Protection of Lines with Surge Diverters

Since surge diverters are devices that provide low resistance paths for overvoltages through an alternate ground path, their operating characteristic and application is of importance.

The spark gap inside the diverter acts as a fast acting switch while non-linear diverter elements provide the low impedance ground path.

The arrester voltage at its terminal when connected to a "line of surge impedance  $Z$  to ground, is given as

The Thevin equivalent circuit for the diverter is shown in Fig. 8.26.

$$V = [2(R+r)/(R+r+Z)] u(t)$$

$Z$  is the line surge impedance,  
 $R$  is the resistance of the non-linear element,  
 $r$  is the ground to earth resistance, and  
 $u(t)$  is the surge voltage.

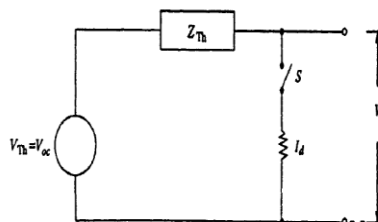


Fig. 8.26 Equivalent circuit of a surge diverter

The switch  $S$  is open for voltages less than the sparkover voltage of the surge diverter  $V_s$ , while it is closed for voltage magnitudes greater than  $V_s$ .

The closing of the switch is represented by injecting a voltage cancellation wave having a negative amplitude equal to the potential difference between the voltage that appears when the switch is open  $V_{oc}$ , and the voltage developed across the impedance of the device after the switch is closed.

$Z_{Th}$  is the impedance of the system viewed from the terminals of the protective device.



6a

HV arm resistance  $R_1 = 16000 \Omega$ .

LV arm " "  $R_2 = \frac{250}{16} \Omega$ .

Terminating resistance  $R_2' = 75 \Omega$ .

Hence, the divider ratio  $a = 1 + \frac{R_1}{R_2} + \frac{R_1}{R_2'}$

$$= 1 + \frac{16000 \times 16}{250} + \frac{16000}{75}$$

$$= 1 + 1024 + 213.3 = 1238.3$$

6b

**Solution:**

$$e = 500 U(t) \text{ kV}$$

$$Z_1 = 500 \Omega$$

$$Z_2 = 60 \Omega$$

**Coefficient of reflection,**

$$\Gamma = \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)} = \frac{(500 - 60)}{(500 + 60)}$$

$$= 0.786$$

**Magnitude of the transmitted wave to the cable**

$$= (1 + \Gamma) e$$

$$= (1.786) \times 500$$

$$= 893 \text{ kV}$$

$$= \text{junction voltage}$$

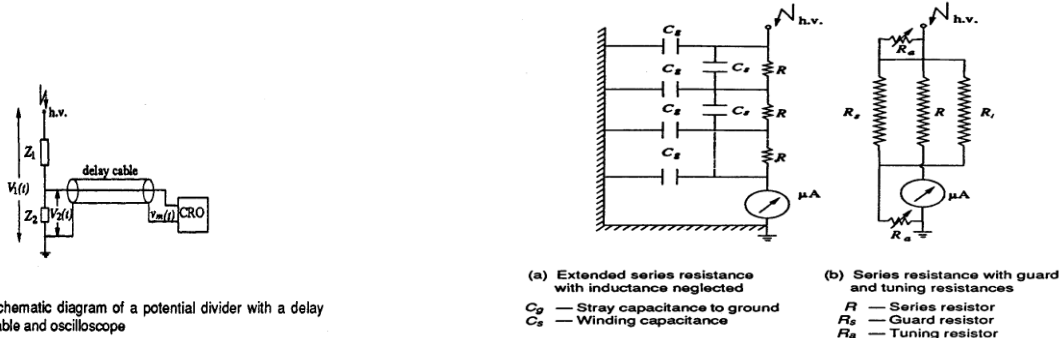
### 7a. Potential Dividers for Impulse Voltage Measurements

- Potential or voltage dividers for high voltage impulse measurements, high frequency a.c. measurements, or for fast rising transient voltage measurements are usually either **resistive** or **capacitive** or **mixed element type**.
- The low voltage arm of the divider is usually connected to a fast recording oscillograph or a peak reading instrument through a delay cable.
- A schematic diagram of a potential divider with its terminating equipment is given in Fig. is usually a **resistor** or a **series of resistors** in case of a **resistance potential divider**, or a **single** or a **number of capacitors** in case of a **capacitance divider**.
- It can also be a combination of both resistors and capacitors.
- $Z_2$  will be a resistor or a capacitor or an R-C impedance depending upon the type of the divider.

- Each element in the divider, in case of high voltage dividers, has a **self\_resistance** or **capacitance**. In addition, the **resistive elements** have **residual inductances**, a **terminal stray capacitance to ground**, and **terminal to terminal capacitances**

$$a = \frac{V_1(t)}{V_2(t)} = 1 + \frac{R_1}{R_2}$$

- The attenuation factor of the divider or the voltage ratio is given by
- The divider element R2, in practice, is connected through the coaxial cable to the oscilloscope.
- The cable will generally have a surge impedance Z0 and this will come in parallel with the oscilloscope input impedance (Rm, Cm).
- the equivalent circuit of the divider with inductance neglected is of the form shown in Fig.



- When a step or fast rising voltage is applied at the high voltage terminal, the voltage developed across the element **Z2** will not have the true waveform as that of the applied voltage. The cable can also introduce distortion in the waveshape
- For high frequency and impulse voltages (since they also contain high frequency fundamental and harmonics), the ratio in the frequency domain will be given by

$$a = \frac{V_1}{V_2} = 1 + \frac{R_1}{(R_2/1 + j\omega R_2 C_m)}$$

- To avoid the frequency dependence of the voltage ratio a, the divider is compensated by adding an additional capacitance C1 across R1.
- The value of C1, to make the divider independent of the frequency, may be obtained from the relation,

$$\frac{R_1}{R_2} = \frac{C_m}{C_1}$$

$$R_1 C_1 = R_2 C_m$$

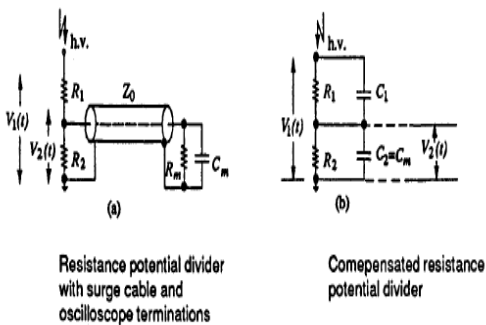


Fig. 7.24 a & b Resistance potential dividers

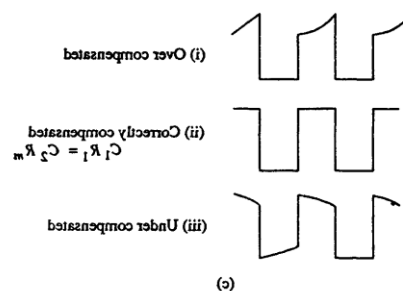
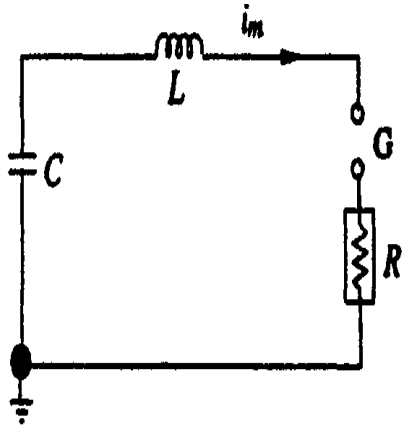


Fig. 7.24c Output of compensated resistance potential divider for different degrees of compensation

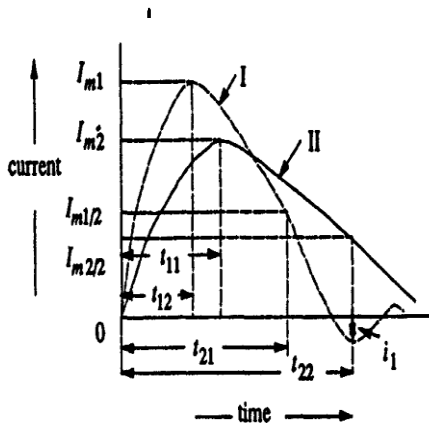
7b

**) Impulse Current Generator:**

- The waveshapes used in testing surge diverters are 4/10 and 8/20  $\mu$ s, representing the nominal wave front and wave tail times
- The tolerances allowed on these times are  $\pm 10\%$  only.



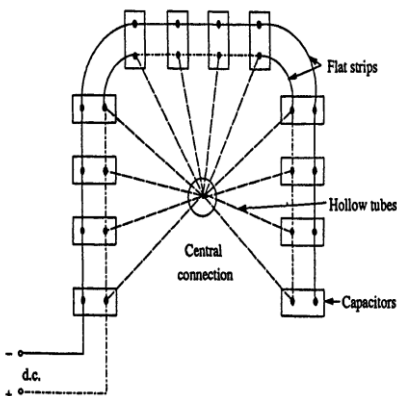
**(a) Basic circuit of an impulse current generator**



$t_1$  and  $t_{12}$  = time-to-front of waves I and II  
 $t_{21}$  and  $t_{22}$  = time-to-tail of waves I and II

- I — damped oscillatory wave
- II — overdamped wave
- $i_1$  — overshoot

**(b) Types of impulse current waveforms**



**(c) Arrangement of capacitors for high impulse current generation**

**Fig. 6.20 Impulse current generator circuit and its waveform**

- If the capacitor is charged to a voltage  $V$  and discharged when the spark gap is triggered, the current  $i_m$  will be given by the equation

$$V = Ri_m + L \frac{di_m}{dt} + \frac{1}{C} \int_0^t i_m dt$$

The circuit is usually underdamped, so that

$$\frac{R}{2} < \sqrt{L/C}$$

$$i_m = \frac{V}{\omega L} [\exp(-\alpha t)] \sin(\omega t) \quad (6.25)$$

where 
$$\alpha = \frac{R}{2L} \text{ and } \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \quad (6.25a)$$

The time taken for the current  $i_m$  to rise from zero to the first peak value is

$$t_1 = t_f = \frac{1}{\omega} \sin^{-1} \frac{\omega}{\sqrt{LC}} = \frac{1}{\omega} \tan^{-1} \frac{\omega}{\alpha} \quad (6.26)$$

The duration for one half cycle of the damped oscillatory wave  $t_2$  is,

$$t_2 = \frac{\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}} \quad (6.27)$$

$$i_m = \frac{V}{\omega L} [\exp(-\alpha t)] \sin(\omega t) \quad (6.25)$$

where 
$$\alpha = \frac{R}{2L} \text{ and } \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \quad (6.25a)$$

The time taken for the current  $i_m$  to rise from zero to the first peak value is

$$t_1 = t_f = \frac{1}{\omega} \sin^{-1} \frac{\omega}{\sqrt{LC}} = \frac{1}{\omega} \tan^{-1} \frac{\omega}{\alpha} \quad (6.26)$$

The duration for one half cycle of the damped oscillatory wave  $t_2$  is,

$$t_2 = \frac{\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}} \quad (6.27)$$

$$L = L_0 + \frac{L_1}{n} + \frac{L_2}{n_1 n_2}$$