A REFERENCE MANUAL ON HIGH VOLTAGE ENGINEERING

COMPLETELY BASED ON LATEST SYALLABUS OF ELECTRICAL AND ELECTONICS ENGINEERING(IV/II), POKHARA UNIVERSITY

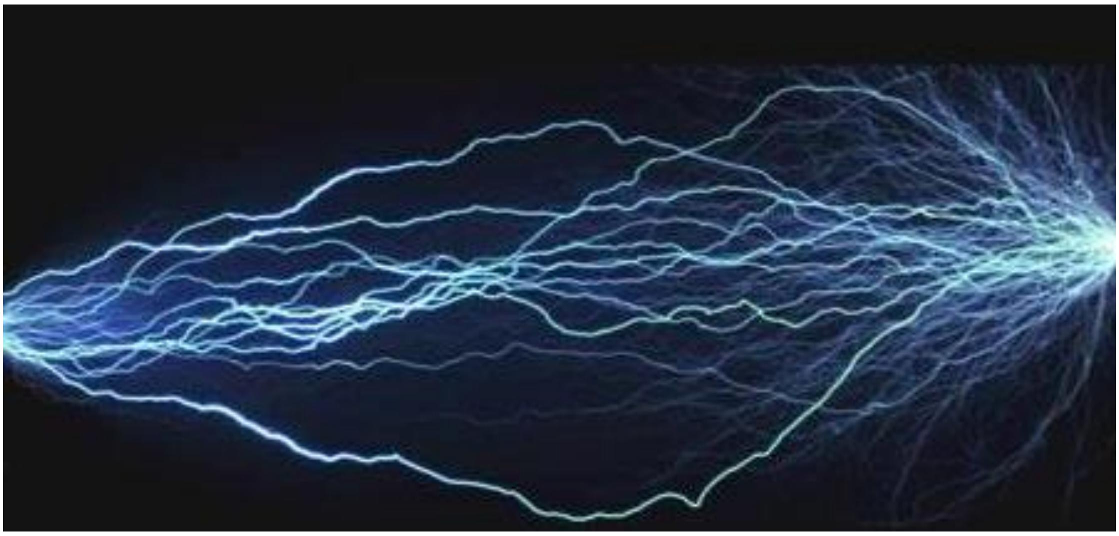

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Table of Contents

UNIT 1 GENERATION OF HIGH VOLTAGES AND CURRENTS

1.1 Generation of High Dc Voltages

There are various applications of high dc voltages in industries, research medical sciences etc. HVDC transmission over both overhead lines and underground cables is becoming more and more popular. HVDC is used for testing HVAC cables of long lengths as these have very large capacitance and would require very large values of currents if tested on HVAC voltages. In industry it is being used for electrostatic precipitation of ashing in thermal power plants, electrostatic painting, cement industry, communication systems etc. The most efficient method of generating high D.C. voltages is through the process of rectification employing voltage multiplier circuits. Electrostatic generators have also been used for generating high D.C. voltages.

Rectifier

The simplest circuit for generation of high direct voltage is the half wave rectifier shown in Figure. Here *RL* is the load resistance and *C* the capacitance to smoothen the dc output voltage. If the capacitor is not connected, pulsating d.c. voltage is obtained at the output terminals whereas with the capacitance *C*, the pulsation at the output terminal are reduced. Assuming the ideal transformer and small internal resistance of the diode during conduction the capacitor *C* is charged to the maximum voltage *Vmax* during conduction of the diode *D.*

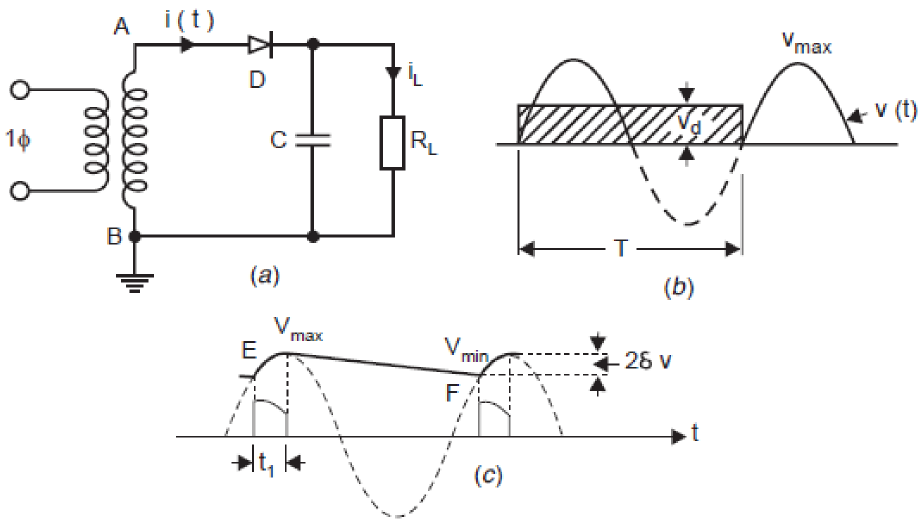
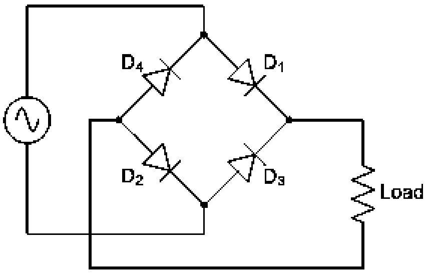


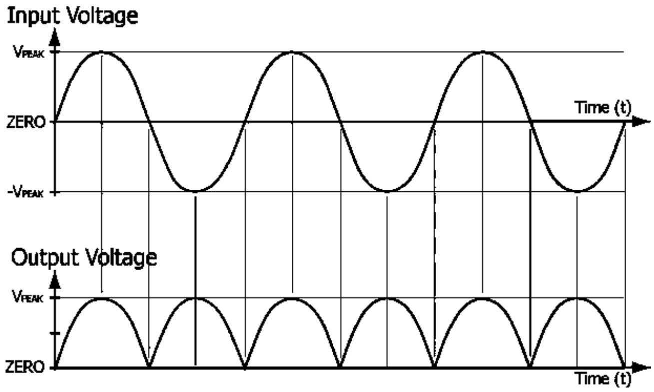
Fig. (*a*) Single Phase rectifier (*b*) Output voltage without *C* (*c*) Output voltage with *C*

Full Wave Rectifier

A bridge rectifier is an arrangement of four diodes in a bridge circuit configuration which provides the same output polarity for either input polarity. It is used for converting an alternating current (AC) input into a direct current (DC) output. For, the positive half cycle, D1 and D2 remain forward biased, while D3 and D4 are reversed biased. So, current flows the path (Source - D1 - Load - D2- Source) and positive polarity appears across the load.

In the negative cycle, D3 and D4 remain forward biased while other two remains forward. And current flows the path(Source - D3 - Load - D4 - Source) and positive polarity appears across the load even the input is of negative polarity. And the output waveforms of it is shown below.





Greinarcher voltage doubler circuits

DC high voltage is usually generated by voltage doubler circuit as shown in figure. During negative half cycle of AC voltage, D_1 conducts there by charging the capacitor C_1 to V_m with polarity. During next positive half cycle terminal A of the capacitor C_1 rises to V_m and hence terminal 'M' attains a potential of $2V_m$. Thus, the capacitor C_2 is charged to $2V_m$ through D_2.

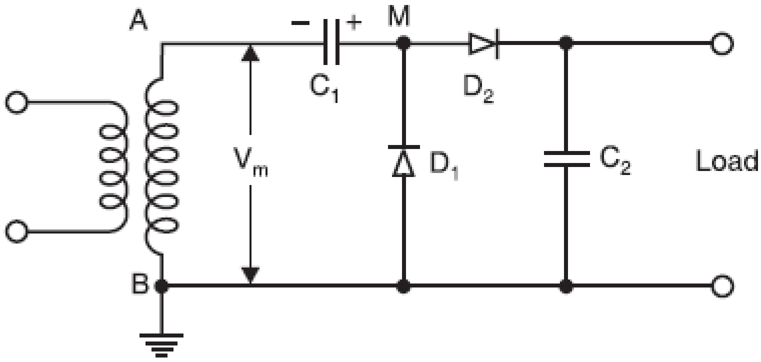


Fig. voltage doubler circuit

Cockroft-Walton Circuit (Voltage Multiplier circuit)

In 1932, Cockroft and Walton suggested an improvement over the circuit developed by Greinacher for producing high D.C. voltages. Fig. 2.3. shows a multistage single phase cascade circuit of the Cockroft-Walton type.

No Load Operation: The portion ABM′MA is exactly indentical to Greinarcher voltage doubler circuit and the voltage across C becomes $2V_{max}$ when M attains a voltage $2V_{max}$.

During the next half cycle when B becomes positive with respect to A, potential of M falls and, therefore, potential of N also falls becoming less than potential at M' hence C_2 is charged through D_2. Next half cycle A becomes more positive and potential of M and N rise thus charging C'_2 through D'_2. Finally all the capacitors C'_1, C'_2, C'_3, C_1, C_2, and C_3 are charged. The voltage across the column of capacitors consisting of C_1, C_2, C_3, keeps on oscillating as the supply voltage alternates. This column, therefore, is known as *oscillating column*. However, the voltage across the capacitances C'_1, C'_2, C'_3, remains constant and is known as *smoothening column*. The voltages at M', N', and O' are $2V_{max}$ $4V_{max}$ and $6V_{max}$. Therefore, voltage across all the capacitors is $2V_{max}$ except for C_1 where it is V_{max} only. The total output voltage is $2nV_{max}$ where n is the number of stages. Thus, the use of multistages arranged in the manner shown enables very high voltage to be obtained. The equal stress of the elements (both capacitors and diodes) used is very helpful and promotes a modular design of such generators.

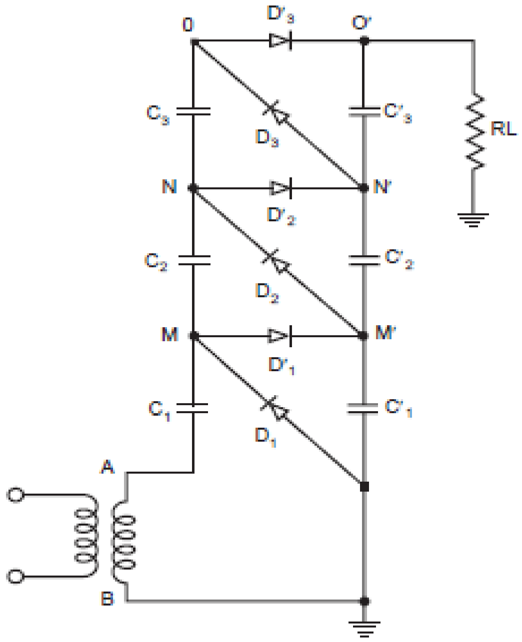


Fig. 2.3

Generator Loaded: When the generator is loaded, the output voltage will never reach the value $2nV_{max}$. Also, the output wave will consist of ripples on the voltage. Thus, we have to deal with two quantities, the voltage drop ΔV and the ripple δV.

Suppose a charge q is transferred to the load per cycle. This charge is $q = I/f = IT$. The charge comes from the smoothening column, the series connection of C'_1, C'_2, C'_3. If no charge were transferred during T from this stack via D_1, D_2, D_3, to the oscillating column, the peak to peak ripple would merely be

$$2\delta V = IT \sum_{n=0}^{n} \frac{1}{C'_i} \qquad (2.6)$$

But in practice charges are transferred. The process is explained with the help of circuits in Fig. 2.4 (*a*) and (*b*).

Fig. 2.4 (*a*) shows arrangement when point A is more positive with reference to B and charging of smoothing column takes place and Fig. 2.4 (*b*) shows the arrangement when in the next half cycle B becomes positive with reference to A and charging of oscillating column takes place. Refer to Fig. 2.4 (*a*). Say the potential of point O' is now $6V_{max}$. This discharges through the load resistance and say the charge lost is $q = IT$ over the cycle. This must be regained during the charging cycle (Fig. 2.4 (*a*)) for stable operation of the generator. C_3 is, therefore supplied a charge q from C_3. For this C_2 must acquire a charge of $2q$ so that it can supply q charge to the load and q to C_3, in the next half cycle termed by cockroft and Walton as the transfer cycle (Fig. 2.4 (*b*)). Similarly C'_1 must acquire for stability reasons a charge $3q$ so that it can supply a charge q to the load and $2q$ to the capacitor C_2 in the next half cycle (transfer half cycle).

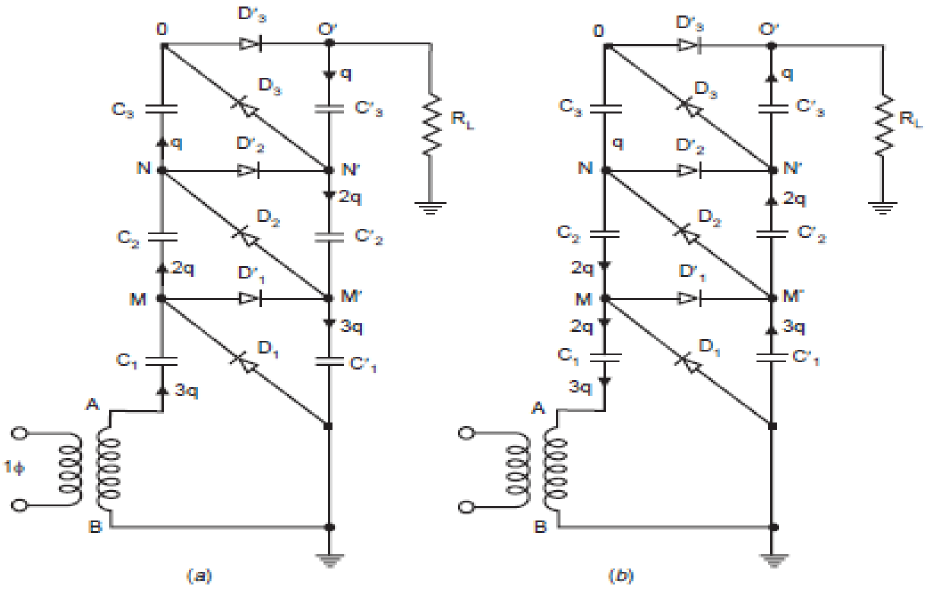


Fig. 2.4 (*a*) Charging of smoothening Column (*b*) Charging of oscillating column

During the transfer cycle shown in Fig. 2.4 (*b*), the diodes D_1, D_2, D_3, conduct when B is positive with reference to A. Here C'_2 transfers q charge to C_3, C_1 transfers charge $2q$ to C_2 and the transformer provides change $3q$.

For n-stage circuit, the total ripple will be

$$2\delta V = \frac{I}{f}\left(\frac{1}{C'_n} + \frac{2}{C'_{n-1}} + \frac{3}{C'_{n-2}} + \ldots + \frac{n}{C'_1}\right)$$

or

$$\delta V = \frac{I}{2f}\left(\frac{1}{C'_n} + \frac{2}{C'_{n-1}} + \frac{3}{C'_{n-2}} + \ldots + \frac{n}{C'_1}\right) \qquad (2.7)$$

From equation (2.7), it is clear that in a multistage circuit the lowest capacitors are responsible for most ripple and it is, therefore, desirable to increase the capacitance in the lower stages. However, this is objectionable from the view point of High Voltage Circuit where if the load is large and the load voltage goes down, the smaller capacitors (within the column) would be overstressed. Therefore, capacitors of equal value are used in practical circuits *i.e.*, $C'_n = C'_{n-1} = \ldots C'_1 = C$ and the ripple is given as

$$\delta V = \frac{I}{2fC}\frac{n(n+1)}{2} = \frac{In(n+1)}{4fC} \qquad (2.8)$$

The second quantity to be evaluated is the voltage drop ΔV which is the difference between the theoretical no load voltage $2nV_{max}$ and the onload voltage. In order to obtain the voltage drop ΔV refer to Fig. 2.4 (*a*).

Here C'_1 is not charged upto full voltage $2V_{max}$ but only to $2V_{max} - 3q/C$ because of the charge given up through C_1 in one cycle which gives a voltage drop of $3q/C = 3I/fC$

The voltage drop in the transformer is assumed to be negligible. Thus, C_2 is charged to the voltage

$$\left(2V_{max} - \frac{3I}{fC}\right) - \frac{3I}{fC}$$

since the reduction in voltage across C'_3 again is $3I/fC$. Therefore, C'_2 attains the voltage

$$2V_{max} - \left(\frac{3I + 3I + 2I}{fC}\right)$$

In a three stage generator

$$\Delta V_1 = \frac{3I}{fC}$$

$$\Delta V_2 = \{2 \times 3 + (3-1)\}\frac{I}{fC}$$

$$\Delta V_3 = (2 \times 3 + 2 \times 2 + 1)\ \frac{I}{fC}$$

In general for a n-stage generator

$$\Delta V_n = \frac{nI}{fC}$$

$$\Delta V_{n-1} = \frac{I}{fC}\ \{2n + (n-1)\}$$

$$\Delta V_{n-2} = \frac{I}{fC}\ \{2n + 2\,(n-1) + (n-2)\}$$

$$\vdots$$

$$\Delta V_1 = \frac{I}{fC}\ \{2n + 2\,(n-1) + 2\,(n-2) + \ldots 2 \times 3 + 2 \times 2 + 1\}$$

$$\Delta V = \Delta V_n + \Delta V_{n-1} + \ldots + \Delta V_1$$

After omitting I/fC, the series can be rewritten as:

$$T_n = n$$
$$T_{n-1} = 2n + (n-1)$$
$$T_{n-2} = 2n + 2\,(n-1) + (n-2)$$
$$T_{n-3} = 2n + 2\,(n-1) + 2\,(n-2) + (n-3)$$
$$\vdots$$
$$T_1 = 2n + 2\,(n-1) + 2\,(n-2) + \ldots + 2 \times 3 + 2 \times 2 + 1$$
$$T = T_n + T_{n-1} + T_{n-2} + \ldots + T_1$$

To sum up we add the last term of all the terms (T_n through T_1) and again add the last term of the remaining term and so on, *i.e.*,

$$
\begin{aligned}
&[n + (n-1) + (n-2) + \ldots + 2 + 1] \\
&+ [2n + 2\,(n-1) + 2\,(n-2) + \ldots + 2 \times 2] \\
&+ [2n + 2\,(n-1) + \ldots + 2 \times 4 + 2 \times 3] \\
&+ [2n + 2\,(n-1) + \ldots + 2 \times 4] \\
&+ [2n + 2\,(n-1) + 2\,(n-2) + \ldots + 2 \times 5] + \ldots [2n]
\end{aligned}
$$

Rearranging the above terms we have

$$
\begin{aligned}
&n + (n-1) + (n-2) + \ldots + 2 + 1 \\
&+ [2n + 2\,(n-1) + 2\,(n-2) + \ldots + 2 \times 2 + 2 \times 1] - 2 \times 1 \\
&+ [2n + 2\,(n-1) + 2\,(n-2) + \ldots + 2 \times 3 + 2 \times 2 + 2 \times 1] - 2 \times 2 - 2 \times 1 \\
&+ [2n + 2\,(n-1) + 2\,(n-2) + \ldots + 2 \times 4 + 2 \times 3 + 2 \times 2 + 2 \times 1] \\
&- 2 \times 3 - 2 \times 2 - 2 \times 1
\end{aligned}
$$

$$\vdots$$

$$
\begin{aligned}
&[2 \times n + 2\,(n-1) + \ldots + 2 \times 2 + 2 \times 1] - [2\,(n-1)] \\
&\quad + 2\,(n-2) + \ldots + 2 \times 2 + 2 \times 1]
\end{aligned}
$$

or $\quad n + (n-1) + (n-2) + \ldots + 2 + 1$

Plus $(n-1)$ number of terms of 2 $[n + (n-1) + \ldots + 2 + 1]$

minus 2 $[1 + (1+2) + (1+2+3) + \ldots + \ldots \{1+2+3+\ldots(n-1)\}]$

The last term (minus term) is rewritten as

$$2\,[1 + (1+2) + \ldots + \{1+2+3+\ldots(n-1)\} + \{1+2+\ldots+n\}]$$
$$-\,2\,[1+2+3+\ldots+n]$$

The nth term of the first part of the above series is given as

$$t_n = \frac{2n\,(n+1)}{2} = (n^2 + n)$$

Therefore, the above terms are equal to

$$= \sum (n^2 + n) - 2 \sum n$$
$$= \sum (n^2 - n)$$

Taking once again all the term we have

$$T = \sum n + 2\,(n-1) \sum n - \sum (n^2 - n)$$
$$= 2n \sum n - \sum n^2$$
$$= 2n \,.\, \frac{n\,(n+1)}{2} - \frac{n\,(n+1)\,(2n+1)}{6}$$
$$= \frac{6\,(n^3 + n^2) - n\,(2n^2 + 3n + 1)}{6}$$
$$= \frac{6n^3 + 6n^2 - 2n^3 - 3n^2 - n}{6}$$
$$= \frac{4n^3 + 3n^2 - n}{6} = \frac{2}{3}n^3 + \frac{n^2}{2} - \frac{n}{6} \qquad (2.9)$$

Here again the lowest capacitors contribute most to the voltage drop ΔV and so it is advantageous to increase their capacitance in suitable steps. However, only a doubling of C_1 is convenient as this capacitors has to withstand only half of the voltage of other capacitors. Therefore, ΔV_1 decreases by an amount nI/fC which rreduces ΔV of every stage by the same amount *i.e.*, by

$$n \,.\, \frac{nI}{2\,fC}$$

Hence
$$\Delta V = \frac{I}{fC}\left(\frac{2}{3}n^3 - \frac{n}{6}\right) \qquad (2.10)$$

If $n \geq 4$ we find that the linear term can be neglected and, therefore, the voltage drop can be approximated to

$$\Delta V \approx \frac{I}{fC} \cdot \frac{2}{3} n^3 \qquad (2.11)$$

The maximum output voltage is given by

$$V_{0\,max} = 2nV_{max} - \frac{I}{fC} \cdot \frac{2}{3} n^3 \qquad (2.12)$$

From (2.12) it is clear that for a given number of stages, a given frequency and capacitance of each stage, the output voltage decrease linearily with load current I. For a given load, however, $V_0 = (V_{0max} - V)$ may rise initially with the number of stages n, and reaches a maximum value but decays beyond on optimum number of stage. The optimum number of stages assuming a constant V_{max}, I, f and C can be obtained for maximum value of $V_{0\,max}$ by differentiating equation (2.12) with respect to n and equating it to zero.

$$\frac{dV_{max}}{dn} = 2V_{max} - \frac{2}{3}\frac{I}{fC}3n^2 = 0$$

$$= V_{max} - \frac{I}{fC}n^2 = 0$$

or

$$n_{opt} = \sqrt{\frac{V_{max}fC}{I}} \qquad (2.13)$$

Substituting n_{opt} in equation (2.12) we have

$$(V_{0\,max})_{max} = \sqrt{\frac{V_{max}fC}{I}}\left(2V_{max} - \frac{2I}{3fC}\frac{V_{max}fC}{I}\right)$$

$$= \sqrt{\frac{V_{max}fC}{I}}\left(2V_{max} - \frac{2}{3}V_{max}\right)$$

$$= \sqrt{\frac{V_{max}fC}{I}} \cdot \frac{4}{3}V_{max} \qquad (2.14)$$

It is to be noted that in general it is more economical to use high frequency and smaller value of capacitance to reduce the ripples or the voltage drop rather than low frequency and high capacitance.

Cascaded generators of Cockroft-Walton type are used and manufactured world-wide these days. A typical circuit is shown in Figure 1. In general, a direct current up to 20 mA is required for high voltages between 1 MV and 2 MV. In case where a higher value of current is required, symmetrical cascaded rectifiers have been developed. These consist of mainly two rectifiers in cascade with a common smoothing column. The symmetrical cascaded rectifier has a smaller voltage drop and also a smaller voltage ripple than the simple cascade. The alternating current input to the individual circuits must be provided at the appropriate high potential; this can be done by means of isolating transformer. Figure 2 shows a typical cascaded rectifier circuit. Each stage consists of one transformer which feeds two half wave rectifiers.

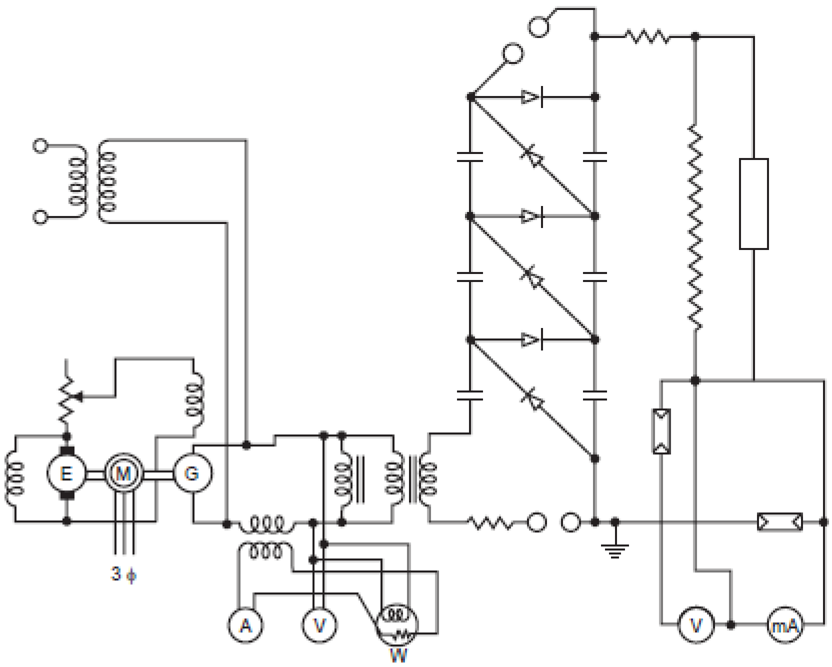


Fig. 1 A typical Cockroft circuit

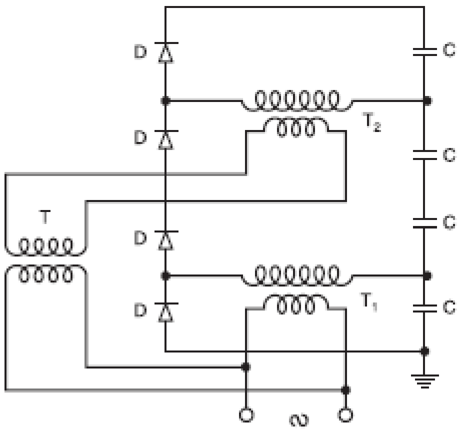


Fig. 2 Cascaded rectifier circuit

As the storage capacitors of these half wave rectifiers are series connected even the hv winding of *T*1 cannot be grounded. This means that the main insulation between the primary and the secondary winding of *T*1 has to be insulated for a dc voltage of magnitude *Vmax*, the peak voltage of *T*1. The same is required for *T*2 also but this time the high voltage winding is at a voltage of 3*Vmax*. It would be difficult to provide the whole main insulation within this transformer, an isolating transformer *T* supplies *T*2. The cascading of every stage would thus require an additional isolating transformer which makes this circuit less economical for more than two stages.

1.2 Generation of High Ac Voltages

Most of the present day, transmission and distribution networks are operating on ac voltages and hence most of the testing equipment's relate to high ac voltages. Even though most of the equipment's on the system are 3-phase systems, a single-phase transformer operating at power frequency is the most common form of HVAC testing equipment. Test transformers normally used for the purpose have low power rating but high voltage ratings. These transformers are mainly used for short time tests on high voltage equipment's.

Cascade transformers

For voltages higher than 400 KV, it is desired to cascade two or more transformers depending upon the voltage requirements. With this, the weight of the whole unit is subdivided into single units and, therefore, transport and erection become easier.

Figure shows a basic scheme for cascading three transformers. The primary of the first stage transformer is connected to a low voltage supply. A voltage is available across the secondary of this transformer. The tertiary winding (excitation winding) of first stage has the same number of turns as the primary winding and feeds the primary of the second stage transformer. The potential of the tertiary is fixed to the potential *V* of the secondary winding as shown in Figure. The secondary winding of the second stage transformer is connected in series with the secondary winding of the first stage transformer, so that a voltage of 2*V* is available between the ground and the terminal of secondary of the second stage transformer. Similarly, the stage-III transformer is connected in series with the second stage transformer. With this the output voltage between ground and the third stage transformer, secondary is 3*V*. it is to be noted that the individual stages except the upper most must have three-winding transformers.

The upper most, however, will be a two-winding transformer. Figure shows metal tank construction of transformers and the secondary winding is not divided. Here the low voltage terminal of the secondary winding is connected to the tank. The tank of stage-I transformer is earthed. The tanks of stage-II and stage-III transformers have potentials of *V* and 2*V*, respectively above earth and, therefore, these must be insulated from the earth with suitable solid insulation. Through h.t. bushings, the leads from the tertiary winding and the hv winding are brought out to be connected to the next stage transformer.

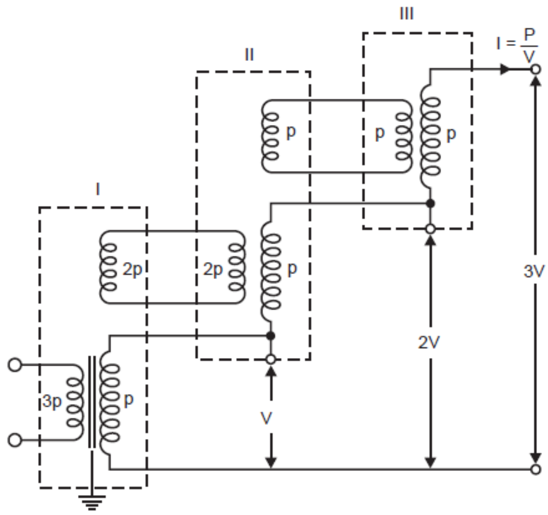
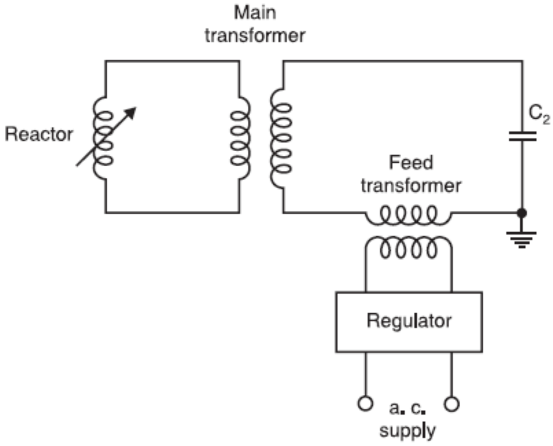


Fig. Basic 3 stage cascaded transformer

Resonant transformer

Whenever the requirement of the test voltage is too much high, a single unit transformer cannot produce such high voltage very economically, because for high voltage measurement, a single unit transformer construction becomes difficult and costly due to insulation problems. Moreover, transportation and erection of large transformer becomes difficult. To overcome these drawbacks, cascading of transformer is done. But cascading of transformer has also some disadvantages such as design is complicated, size is bulky, costly, losses are more (summation of individual transformer) and hence efficiency reduces.

Resonant transformer is one of the best choice for high voltage generation which operates on resonance phenomenon (XL = Xc). If *N* is the transformation ratio and *L* is the inductance on the low voltage side of the transformer, then it is reflected with *N*2 *L* value on the secondary side (load side) of the transformer. For certain setting of the reactor, the inductive reactance may equal the capacitive reactance of the circuit, hence resonance will take place. Thus, the reactive power requirement of the supply becomes zero and it has to supply only the losses of the circuit. However, the transformer has to carry the full load current on the high voltage side. This is a disadvantage of the method. The inductors are designed for high quality factors $Q = \omega L/R$. The feed transformer, therefore, injects the losses of the circuit only.



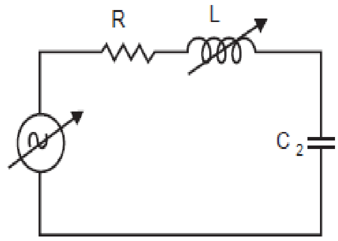


Figure represents an equivalent circuit for series resonance circuit. Here R is usually of low value. After the resonance condition is achieved, the output voltage can be increased by increasing the input voltage. The feed transformers are rated for nominal current ratings of the reactor.
Under resonance, the output voltage will be

$$V_0 = \frac{V}{R}\frac{1}{\omega C_2}$$

Where V is the supply voltage.

Since at resonance

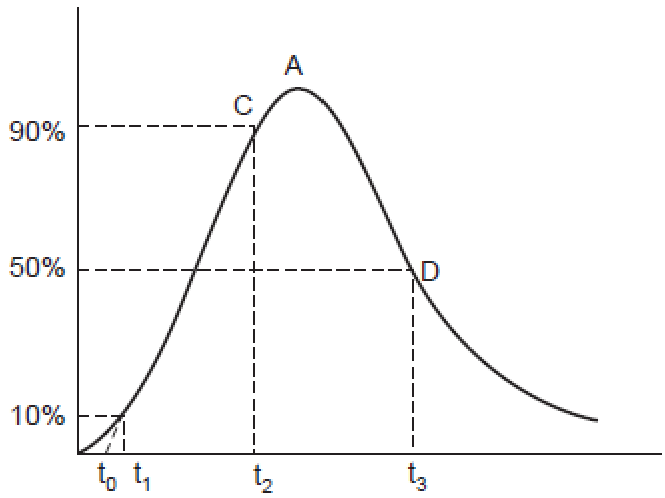
$$\omega L = \frac{1}{\omega C_2}$$

Therefore $$V_0 = \frac{V}{R}\omega L = VQ$$

where Q is the quality factor of the inductor which usually varies between 40 and 80. This means that with $Q = 40$, the output voltage is 40 times the supply voltage.

1.3 Generation of Impulse Voltages

An impulse voltage is a unidirectional voltage which, without appreciable oscillations, rises rapidly to a maximum value and falls more or less rapidly to zero Figure. The maximum value is called the peak value of the impulse and the impulse voltage is specified by this value. The wave front time of an impulse wave is the time taken by the wave to reach to its maximum value starting from zero value. Usually it is difficult to identify the start and peak points of the wave and, therefore, the wave front time is specified as 1.25 times ($t2 – t1$), where $t2$ is the time for the wave to reach to its 90% of the peak value and $t1$ is the time to reach 10% of the peak value. Since ($t2 – t1$) represents about 80% of the wave front time, it is multiplied by 1.25 to give total wave front time.
The nominal wave tail time is measured between the nominal starting point $t0$ and the point on the wave tail where the voltage is 50% of the peak value *i.e.* wave fail time is expressed as ($t3 – t0$).



The standard wave shape specified in BSS and ISS is a 1/50 micro sec. wave *i.e.* a wave front of 1 micro sec and a wave tail of 50 micro sec.

Impulse Generator Circuits

Figure represents an exact equivalent circuit of a single stage impulse generator along with a typical load.

*C*1 is the capacitance of the generator charged from a dc source to a suitable voltage which causes discharge through the sphere gap. The capacitance *C*1 may consist of a single capacitance, in which case the generator is known as a single stage generator or alternatively if *C*1 is the total capacitance of a group of capacitors charged in parallel and then discharged in series, it is then known as a multistage generator.

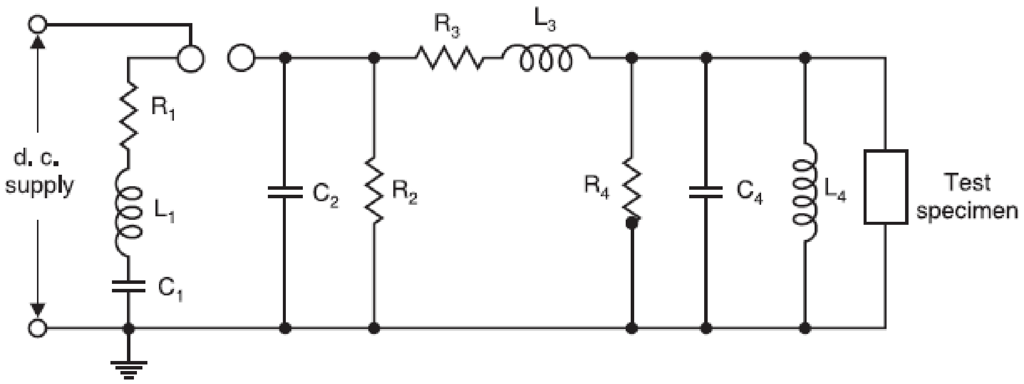


Fig. Exact equivalent circuit of a single stage impulse generator with a typical load

*L*1 is the inductance of the generator and the leads connecting the generator to the discharge circuit and is usually kept as small as possible. The resistance *R*1 consists of the inherent series resistance of the capacitances and leads and often includes additional lumped resistance inserted within the generator for damping purposes and for output waveform control. *L*3, *R*3 are the external elements which may be connected at the generator terminal for waveform control. *R*2 and *R*4 control the duration of the wave. However, *R*4 also serves as a potential divider when a CRO is used for measurement purposes. *C*2 and *C*4 represent the capacitances to earth of the high voltage components and leads. *C*4 also includes the capacitance of the test object and of any other load capacitance required for producing the required wave shape. *L*4 represents the inductance of the test object and may also affect the wave shape appreciably.

Two simplified but more practical forms of impulse generator circuits are shown in Figure (*a*) and (*b*).

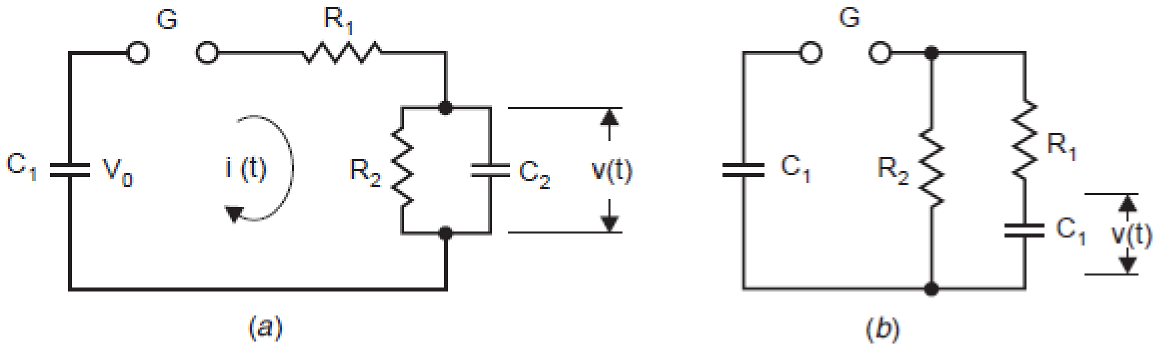
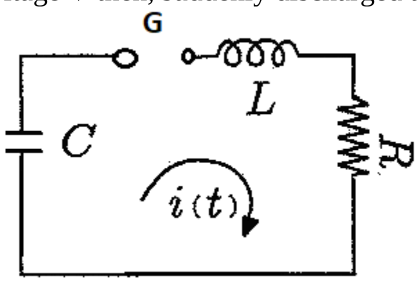


Fig. Simplified equivalent circuit of an impulse generator

The two circuits are widely used and differ only in the position of the wave tail control resistance *R*2. When *R*2 is on the load side of *R*1 (Fig. *a*) the two resistances form a potential divider, which reduces the output voltage but when *R*2 is on the generator side of *R*1 (Fig. *b*) this particular loss of output voltage is absent. The impulse capacitor *C*1 is charged through a charging resistance (not shown) to a dc voltage *V*0 and then discharged by flashing over the switching gap with a pulse of suitable value. The desired impulse voltage appears across the load capacitance *C*2. The value of the circuit elements determines the shape of the output impulse voltage.

Analysis of impulse generator circuit of series RLC type

RLC series circuit can be used for model generator only. Capacitance C of the generator is charged from a dc source to a suitable voltage V then, suddenly discharged through the sphere gap G.



For RLC series circuit,

$V = \frac{1}{C}\int_0^t i(t) + L\frac{di}{dt} + Ri$

With initial condition at t=0, i(0) = 0 and the net charge in the circuit q = 0

Taking Laplace Transform on both sides

$\frac{V}{s} = \frac{I(s)}{Cs} + LsI(s) + RI(s) = \left[\frac{1}{Cs} + Ls + R\right] I(s) = \frac{LCs^2+RCs+1}{Cs} I(s)$

V = L $[s^2 + \frac{R}{L}s + \frac{1}{LC}]$ I(s)

Current through resistor R

I(s) = $\frac{V}{L\,[s^2+\frac{R}{L}s+\frac{1}{LC}]}$

Output voltage $V_0(s) = R.I(s)$ = $\frac{VR}{L\,[s^2+\frac{R}{L}s+\frac{1}{LC}]}$

Roots of $s^2 + \frac{R}{L}s + \frac{1}{LC}$ are

$\alpha = \frac{-R}{2L} + \sqrt{(\frac{R}{2L})^2 - \frac{1}{LC}}$

$\beta = \frac{-R}{2L} - \sqrt{(\frac{R}{2L})^2 - \frac{1}{LC}}$

For an overdamped case,

$\frac{R}{2L} \geq \frac{1}{\sqrt{LC}}$

The solution of output voltage is

$$V_0(t) = \frac{RV}{2L\sqrt{(\frac{R}{2L})^2-\frac{1}{LC}}}(e^{-\alpha t} - e^{-\beta t}) = V_0(e^{-\alpha t} - e^{-\beta t})$$

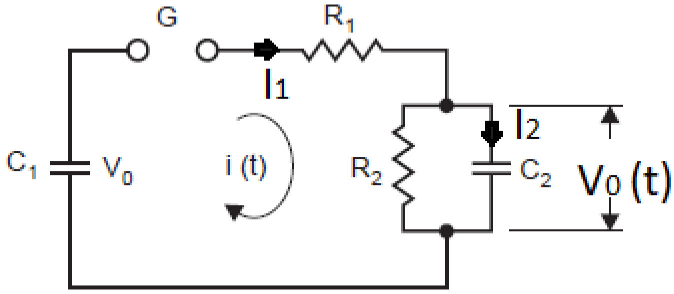
Where,

$$V_0 = \frac{RV}{2L\sqrt{\left(\frac{R}{2L}\right)^2-\frac{1}{LC}}}$$

The sum of roots $(\alpha + \beta) = \frac{-R}{2L}$ and the product of roots $\alpha\beta = \frac{1}{LC}$

Wave front time or β can be determined by choosing suitable value of L and wave tail time or α can be determined by choosing suitable value of R.

Analysis of other impulse generator circuit



Output voltage, $V_0(s) = \frac{1}{sC_2} I_2(s)$ ……….. (1)

$I_2(s) = I_1(s) \times \frac{R_2}{R_2+sC_2}$ ………… (2)

$$\frac{V}{s} = \left[R_1 + \frac{1}{sC_1} + \frac{R_2\times\frac{1}{sC_2}}{R_2+sC_2}\right] I_1(s)$$

$$I_1(s) = \frac{\frac{V}{s}}{R_1+\frac{1}{sC_1}+\frac{R_2\times\frac{1}{sC_2}}{R_2+sC_2}} \text{ ……… (3)}$$

Substituting the value of $I_2(s)$ in equation (1) from equation (2)

$$V_0(s) = \frac{1}{sC_2} I_1(s) \times \frac{R_2}{R_2+sC_2}$$

Substituting the value of $I_1(s)$ from equation (3)

$$V_0(s) = \frac{1}{sC_2} I_1(s) = \frac{\frac{V}{s}}{R_1+\frac{1}{sC_1}+\frac{R_2\times\frac{1}{sC_2}}{R_2+sC_2}} \times \frac{R_2}{R_2+sC_2}$$

$$= \frac{1}{sC_2}\frac{V}{s}\frac{1}{R_1R_2+\frac{1}{s^2C_1C_2}+\frac{R_1}{sC_2}+\frac{R_2}{sC_1}+\frac{R_2}{sC_2}} \times R_2$$

$$= \frac{V}{C_2R_1\left\{s^2+s\left(\frac{1}{R_2C_2}+\frac{1}{R_1C_1}+\frac{1}{R_1C_2}\right)+\frac{1}{R_1R_2C_1C_2}\right\}}$$

The characteristics equation becomes

$$s^2 + s\left(\frac{1}{R_2C_2} + \frac{1}{R_1C_1} + \frac{1}{R_1C_2}\right) + \frac{1}{R_1R_2C_1C_2} = 0$$

The sum of roots $(\alpha + \beta) = -\left(\frac{1}{R_2C_2} + \frac{1}{R_1C_1} + \frac{1}{R_1C_2}\right)$

The product of roots $\alpha\beta = \frac{1}{R_1R_2C_1C_2}$

$\frac{1}{R_1C_1}$ and $\frac{1}{R_2C_2}$ will be small as compared with $\frac{1}{R_1C_2}$ so it may be neglected.

By solving, the approximate value of $\alpha = \frac{1}{R_1 C_2}$ and $\beta = \frac{1}{R_2 C_1}$

$V_0(s) = \frac{V}{C_2 R_1 (s+\alpha)(s+\beta)}$

Using partial fraction

$V_0(s) = \frac{K_1}{(s+\alpha)} + \frac{K_2}{(s+\beta)}$

$sK_1 + sK_2 + \alpha K_2 + \beta K_1 = \frac{V}{C_2 R_1}$

Equating s terms, we get

$K_1 + K_2 = 0$

$K_1 = -K_2$

Equating constant terms

$\alpha K_2 + \beta K_1 = \frac{V}{C_2 R_1}$

$-\alpha K_1 + \beta K_1 = \frac{V}{C_2 R_1}$

$K_1(\beta - \alpha) = \frac{V}{C_2 R_1}$

$K_1 = \frac{V}{C_2 R_1 (\beta - \alpha)}$

$K_2 = -\frac{V}{C_2 R_1 (\beta - \alpha)}$

$V_0(s) = \frac{V}{C_2 R_1 (\beta-\alpha)(s+\alpha)} - \frac{V}{C_2 R_1 (\beta-\alpha)(s+\beta)}$

Taking Inverse Laplace Transform

$V_0(t) = \frac{V}{C_2 R_1 (\beta-\alpha)} (e^{-\alpha t} - e^{-\beta t})$

Wave front and wave tail are independently controlled by changing either $R_1 or\ R_2$ separately.

Multistage Impulse Generator Circuit

Depending upon the charging voltage available and the output voltage required a number of identical impulse capacitors are charged in parallel and then discharged in series, thus obtaining a multiplied total charging voltage corresponding to the number of stages. The impulse capacitors *C*1 are charged to the charging voltage *V*0 through the high charging resistors *Rc* in parallel. When all the gaps *G* break down, the $C_1{}'$capacitances are connected in series so that *C*2 is charged through the series connection of all the wave front resistances $R_1{}'$and finally all $C_1{}'$and *C*2 will discharge through the resistors $R_2{}'$and $R_1{}'$Usually *Rc* >> *R*2 >> *R*1.

In order that the Marx circuit operates consistently it is essential to adjust the distances between various sphere gaps such that the first gap *G*1 is only slightly less than that of *G*2 and so on. If is also necessary that the axes of the gaps *G* be in the same vertical plane so that the ultraviolet radiations due to spark in the first gap *G*, will irradiate the other gaps. This ensures a supply of electrons released from the gap electrons to initiate breakdown during the short period when the gaps are subjected to over-voltages.

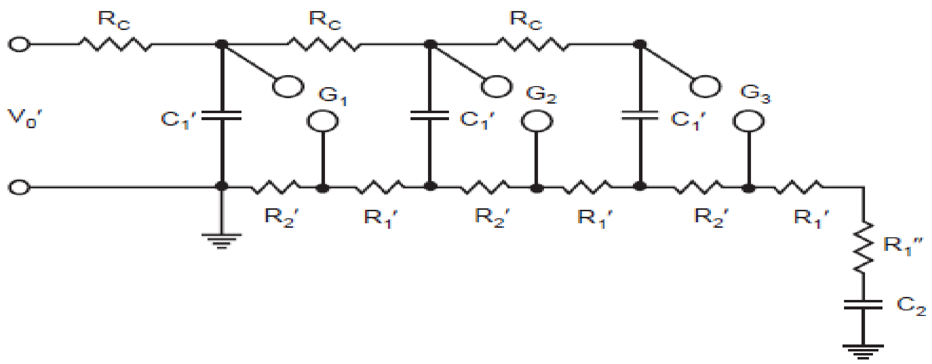
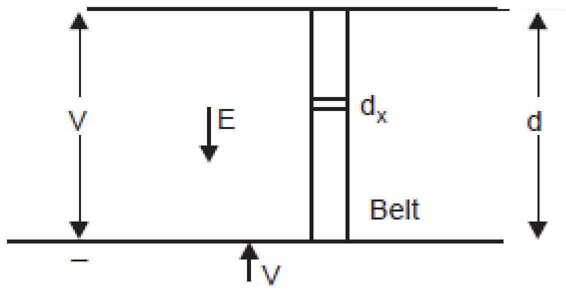


Fig. A 3-stage Marx impulse generator in circuit '*b*' connections.

Vande-Graff Generator

In electromagnetic generators, current carrying conductors are moved against the electromagnetic forces acting upon them. In contrast to the generator, electrostatic generators convert mechanical energy into electric energy directly. The electric charges are moved against the force of electric fields, thereby higher potential energy is gained at the cost of mechanical energy. The basic principle of operation is explained with the help of Figure.



An insulated belt is moving with uniform velocity v in an electric field of strength $E(x)$. Suppose the width of the belt is b and the charge density σ consider a length dx of the belt, the charge $dq = \sigma\, bdx$.

The force experienced by this charge (or the force experienced by the belt).

$$dF = Edq = E\,\sigma\, bdx$$

or
$$F = \sigma b \int E dx$$

Normally the electric field is uniform

$\therefore$
$$F = \sigma b V$$

The power required to move the belt

$$= \text{Force} \times \text{Velocity}$$

$$= Fv = \sigma b V v$$

Now current
$$I = \frac{dq}{dt}\,\sigma b \frac{dx}{dt} = \sigma b v$$

$\therefore$ The power required to move the belt

$$P = Fv = \sigma b V v = VI$$

Assuming no losses, the power output is also equal to VI.

Figure shows belt driven electrostatic generator developed by Van deGraaf in 1931. An insulating belt is run over pulleys. The belt, the width of which may vary from a few cms to metres is driven at a speed of about 15 to 30 m/sec, by means of a motor connected to the lower pulley. The belt near the lower pully is charged electrostatically by an excitation arrangement. The lower charge spray unit consists of a number of needles connected to the controllable d.c. source (10 kV–100 kV) so that the discharge between the points and the belt is maintained. The charge is conveyed to the upper end where it is collected from the belt by discharging points connected to the inside of an insulated metal electrode through which the belt passes. The entire equipment is enclosed in an earthed metal tank filled with insulating gases of good dielectric strength viz. SF6 etc. So that the potential of the electrode could be raised to relatively higher voltage without corona discharges or for a certain voltage a smaller size of the equipment will result. Also, the shape of the h.t., electrode should be such that the surface gradient of electric field is made uniform to reduce again corona discharges, even though it is desirable to avoid corona entirely. An isolated sphere is the most favorable electrode shape and will maintain a uniform field *E* with a voltage of *Er* where *r* is the radius of the sphere.

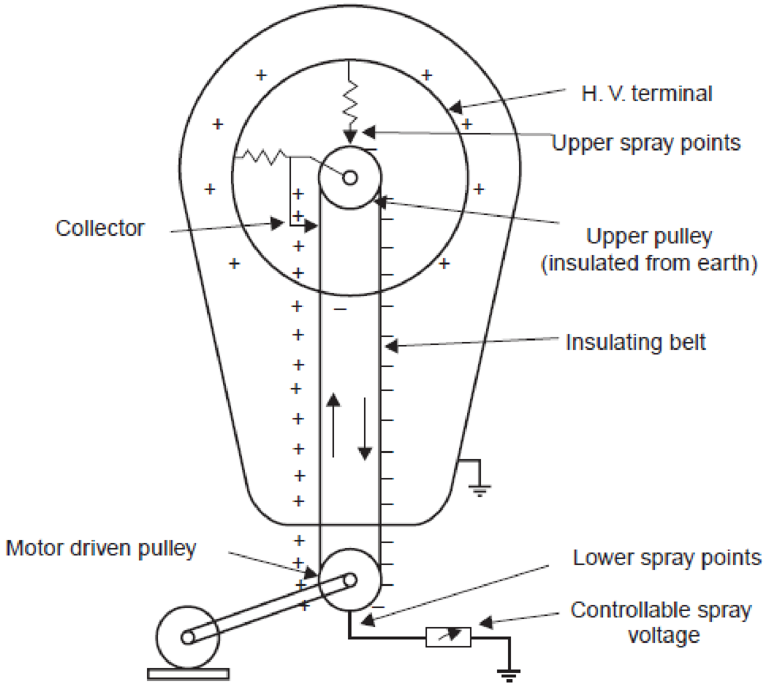


Fig. Van de Graaf generator

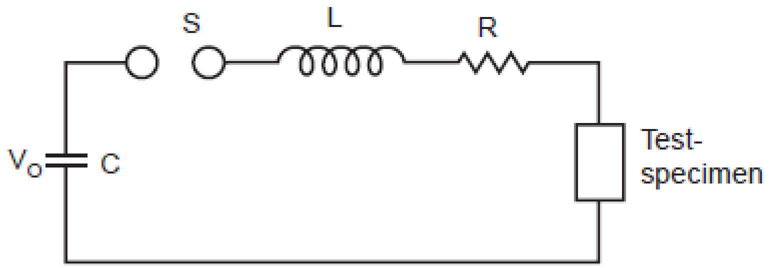
As the h.t. electrode collects charges its potential rises. The potential at any instant is given as $V = q/C$ where q is the charge collected at that instant. It appears as though if the charge were collected for a long time any amount of voltage could be generated. However, as the potential of electrode rises, the field set up by the electrode increases and that may ionise the surrounding medium and, therefore, this would be the limiting value of the voltage. In practice, equilibrium is established at a terminal voltage which is such that the charging current

$$\left(I = C\frac{dV}{dt}\right)$$

equals the discharge current which will include the load current and the leakage and corona loss currents. The moving belt system also distorts the electric field and, therefore, it is placed within properly shaped field grading rings. The grading is provided by resistors and additional corona discharge elements. The collector needle system is placed near the point where the belt enters the h.t. terminal. A second point system excited by a self-inducing arrangement enables the down going belt to be charged to the polarity opposite to that of the terminal and thus the rate of charging of the latter, for a given speed, is doubled. The self-inducing arrangement requires insulating the upper pulley and maintaining it at a potential higher than that of the h.t. terminal by connecting the pulley to the collector needle system. The arrangement also consists of a row of points (shown as upper spray points in Figure) connected to the inside of the h.t. terminal and directed towards the pulley above its points of entry into the terminal. As the pulley is at a higher potential (positive), the negative charges due to corona discharge at the upper spray points are collected by the belt. This neutralizes any remaining positive charge on the belt and leaves an excess of negative charges on the down going belt to be neutralized by the lower spray points. Since these negative charges leave the h.t. terminal, the potential of the h.t. terminal is raised by the corresponding amount.

1.4 Impulse current generation

The impulse current wave is specified on the similar lines as an impulse voltage wave. High current impulse generators usually consist of a large number of capacitors connected in parallel to the common discharge
path. A typical impulse current generator equivalent circuit is shown in Figure and approximates to that of a capacitance *C* charged to a voltage *V*0 which can be considered to discharge through an inductance *L* and a resistance *R*. In practice both *L* and *R* are the effective inductance and resistance of the leads, capacitors and the test objects.



After the gap *S* is triggered, the Laplace transform current is given as

$$I(s) = \frac{V_0}{s} \frac{1}{R + sL + 1/Cs}$$

$$= \frac{V}{L} \cdot \frac{1}{s^2 + R/Ls + 1/LC}$$

$$= \frac{V}{L} \cdot \frac{1}{(s+\alpha)^2 + \omega^2}$$

where $\alpha = \dfrac{R}{2L}$ and $\omega = \left(\dfrac{1}{LC} - \dfrac{R^2}{4L^2}\right)^{1/2}$

or $$\omega = \frac{1}{\sqrt{LC}}\left(1 - \frac{R^2C}{4L}\right)^{1/2} = \frac{1}{\sqrt{LC}}(1-\nu^2)^{1/2}$$

where $$\nu = \frac{R}{2}\sqrt{\frac{C}{L}}$$

Taking the inverse Laplace we have the current

$$i(t) = \frac{V}{\omega L} e^{-\alpha t} \sin \omega t$$

For current $i(t)$ to be maximum $\dfrac{di(t)}{dt} = 0$

$$\frac{di(t)}{dt} = \frac{V}{\omega L}\ [\omega e^{-\alpha t}\cos\omega t - \alpha e^{-\alpha t}\sin\omega t] = 0$$

$$= \frac{V}{\omega L}\ e^{-\alpha t}[\omega\cos\omega t - \alpha\sin\omega t] = 0$$

or
$$\frac{\omega}{\sqrt{\alpha^2+\omega^2}}\cos\omega t - \frac{\alpha}{\sqrt{\alpha^2+\omega^2}}\sin\omega t = 0$$

or $\quad \sin\theta\cos\omega t - \cos\theta\sin\omega t = 0$

or $\quad \sin(\theta - \omega t) = 0$

or $\quad \omega t = \theta$

or
$$t_{max} = \frac{\theta}{\omega}$$

where t_{max} is the time when the first maximum value of current occurs and

$$\theta = \sin^{-1}\frac{\omega}{\sqrt{\alpha^2+\omega^2}}$$

$$= \sin^{-1}\frac{\omega}{\left[\frac{R_2}{4L^2}+\frac{1}{LC}-\frac{R^2}{4L^2}\right]^{1/2}}$$

$$= \sin^{-1}\sqrt{LC\,\omega}$$

or
$$t_{max} = \frac{\sin^{-1}\sqrt{LC\omega}}{\omega} = \frac{\sin^{-1}\sqrt{LC}\,.\,\frac{1}{\sqrt{LC}}(1-\nu^2)^{1/2}}{\frac{1}{\sqrt{LC}}(1-\nu^2)^{1/2}}$$

or
$$t_{max} = \sqrt{LC}(1-\nu^2)^{-1/2}\sin^{-1}(1-\nu^2)^{1/2} = \sqrt{LC}.\frac{\sin^{-1}(1-\nu^2)^{1/2}}{(1-\nu^2)^{1/2}}$$

Substituting the value of $t = t_{max}$ in (3.25) the first maximum value of current is given as

$$I_{max} = \frac{V_0\sqrt{LC}}{(1-\nu^2)^{1/2}L}\,.\,\mathrm{Exp}\left[-\frac{R\sqrt{LC}}{2L}\frac{\sin^{-1}(1-\nu^2)^{1/2}}{(1-\nu^2)^{1/2}}\right]$$

$$\sin\left\{\frac{(1-\nu^2)^{1/2}}{\sqrt{LC}}\,.\,\sqrt{LC}\,(1-\nu^2)^{-1/2}\sin^{-1}(1-\nu^2)^{1/2}\right\}$$

$$= \frac{V_0}{(1-\nu^2)^{1/2}}\cdot\sqrt{\frac{C}{L}}\,.\,\mathrm{Exp}\left[\frac{-\nu\sin^{-1}(1-\nu^2)^{1/2}}{(1-\nu^2)^{1/2}}\right].\sin\left\{\sin^{-1}(1-\nu^2)^{1/2}\right\}$$

$$= V_0\sqrt{\frac{C}{L}}\,\mathrm{Exp}\left[\frac{-\nu\sin^{-1}(1-\nu^2)^{1/2}}{(1-\nu^2)^{1/2}}\right]$$

Above equation can be rewritten as

$$I_{\max} = V_0 \sqrt{\frac{C}{L}} f(\mathrm{v}) = \sqrt{\frac{2W}{L}} f(\mathrm{v})$$

where $$W = \frac{1}{2} C V_0^2$$

the initial energy stored by the generator.

If $R = 0$, v□ = 0

$$i(t) = V_0 \sqrt{\frac{C}{L}} \sin \frac{t}{\sqrt{LC}}$$

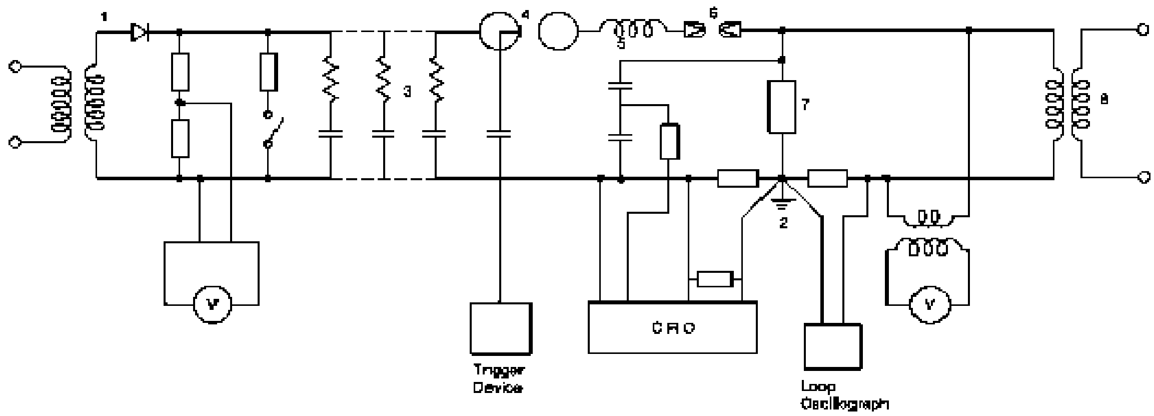


Fig. A typical impulse current generator circuit. 1. Charging unit 2. Earthing device 3. Capacitors with damping resistors 4. Firing sphere gap. 5. Reactor coil 6. Protective sphere gap 7. Test specimen (LA) 8. Test transformer for power frequency.

UNIT 2 MEASUREMENT OF HIGH VOLTAGES AND CURRENTS

Various Techniques for Measuring High Voltages and Currents

Different methods for measurement of high voltages is listed in table below.

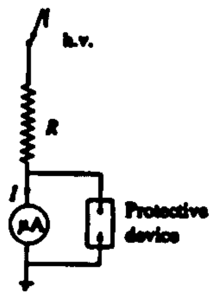
Type of Voltage	**Method or Technique**
DC Voltage	➢ Series resistance microammeter ➢ Resistance potential divider ➢ Generating voltmeter ➢ Sphere and other spark gaps
AC Voltage (Power frequency)	➢ Series impedance ammeters ➢ Potential dividers (resistance and capacitance type) ➢ Potential transformers (electromagnetic or CVT) ➢ Electrostatic voltmeters ➢ Sphere gaps
AC high frequency voltages, Impulse voltages, and other rapidly changing voltages	➢ Potential dividers with a cathode ray oscillograph (resistive or capacitive dividers) ➢ Peak voltmeters ➢ Sphere gaps

Measurement of High DC Voltages

High Ohmic Series Resistance with Microammeter

High dc voltages are usually measured by connecting a very high resistance (few hundreds of megaohms) in series with a microammeter as shown in Fig. Only the current flowing through the large calibrated resistance R is measured by the moving coil microammeter. The voltage of the source is given by V=IR.

The voltage drop in the meter is negligible, as the impedance of the meter is only few ohms compared to few hundred mega-ohms of the series resistance R. A protective device like a paper gap, a neon glow tube, or a Zener diode with a suitable series resistance is connected across the meter as a protection against high voltages in case the series resistance R fails or flashes over. The ohmic value of the series resistance R is chosen such that a current of one to ten microamperes is allowed for full-scale deflection.



The resistance is constructed from a large number of wire wound resistors in series. The voltage drop in each resistor element is chosen to avoid surface flashovers and discharges. A Value less than 5 kV/cm in air or less than 20 kV/cm in good oil is permissible. The resistor chain is provided with corona free terminations. The material for resistive elements is usually a carbon-alloy with temperature coefficient less than 10^{-4}/°C. Carbon and other metallic film resistors are also used. A resistance chain built with ±1% carbon resistors located in an airtight transformer oil filled P.V.C. tube, for 100 kV operation had very good temperature stability.

The limitations in the series resistance design are:

(i) power dissipation and source loading,

(ii) temperature effects and long-time stability,

(iii) voltage dependence of resistive elements, and

(iv) sensitivity to mechanical stresses.

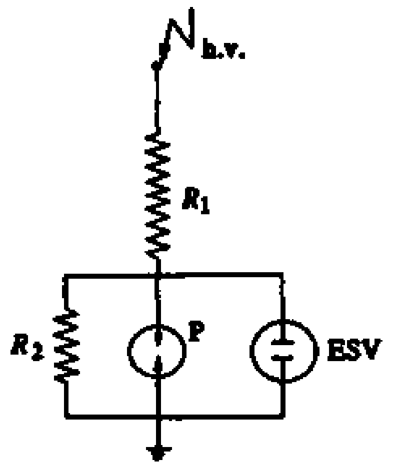
Series resistance meters are built for 500 kV dc with an accuracy better than 0.2%.

Resistance Potential Dividers

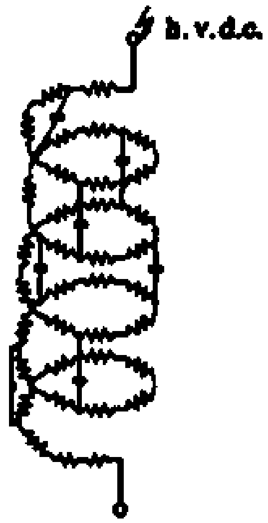
A resistance potential divider with an electrostatic or high impedance voltmeter is shown in Fig. (a). The influence of temperature and voltage on the elements is eliminated in the voltage divider arrangement.

The high voltage magnitude is given by $[(R_1 + R_2)/R_2]\ V_2$, where V_2 is the dc voltage across the low voltage arm R_2.

With sudden changes in voltage, such as switching operations, flashover of the test objects, or source short circuits, flashover or damage may occur to the divider elements due to the stray capacitance across the elements and due to ground capacitances. To avoid such transient voltages, voltage controlling capacitors are connected across the elements. A corona free termination is provided to avoid unnecessary discharges at high voltage ends. A series resistor with a parallel capacitor connection for linearization of transient potential distribution is shown in Fig. (b). Potential dividers are made with 0.05% accuracy up to 100 kV, with 0.1% accuracy up to 300 kV, and with better than 0.5% accuracy for 500 kV.



(a) Resistance potential divider with an electrostatic voltmeter
P - Protective device
ESV - Electrostatic volt-meter



(b) Series resistor with parallel capacitors for potential linearization for transient voltages

Generating Voltmeters

High voltage measuring devices employ generating principle when source loading is prohibited or when direct connection to the high voltage source is to be avoided. A generating voltmeter is a variable capacitor electrostatic voltage generator which generates current proportional to the applied external voltage. The device is driven by an external synchronous or constant speed motor and does not absorb power or energy from the voltage measuring source.

The charge stored in a capacitor of capacitance C is given by q = CV. If the capacitance of the capacitor varies with time when connected to the source of voltage V, the current through the capacitor,

$$i = \frac{dq}{dt} = V\frac{dC}{dt} + C\frac{dV}{dt}$$

For dc Voltages $\frac{dV}{dt} = 0$. Hence, $i = \frac{dq}{dt} = V\frac{dC}{dt}$

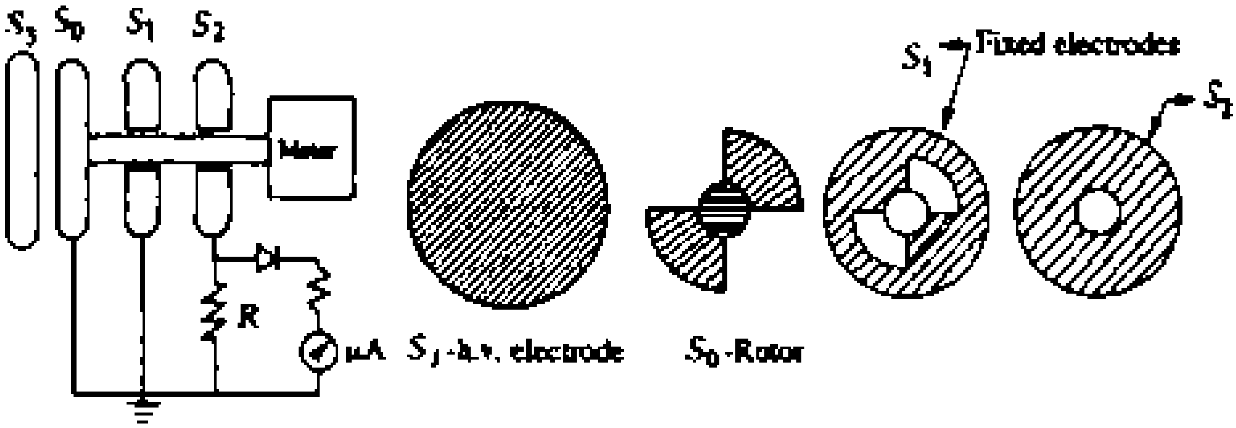
If the capacitances C varies between the limits C_o and (C_o+C_m) sinusoidally as

$C = C_o + C_m \sin \omega t$ w is the angular frequency (z*pi*N/60)

The current I is $i = i_m \cos \omega t$ where, $i_m = VC_m\omega$ is the peak value of the current. The rms value of the current is given by $i_{rms} = \frac{V\omega C_m}{\sqrt{2}}$

For a constant angular frequency, the current is proportional to the applied voltage V. More often, the generated current is rectified and measured by a moving coil meter. Generating voltmeter can be used for ac voltage measurements also provided the angular frequency O) is the same or equal to half that of the supply frequency.

Generating voltmeters employ rotating sectors or vanes for variation of capacitance. The high voltage source is connected to a disc electrode S_3 which is kept at a fixed distance on the axis of the other low voltage electrodes S_0, S_1 and S_2. The rotor S_0 is driven at a constant speed by a synchronous motor at a suitable speed (1500, 1800, 3000, or 3600 rpm). The rotor vanes of S_0 cause periodic change in capacitance between the insulated disc S_2 and the hv electrode S_3. The shape and number of the vanes of S_0 and S_1 are so designed that they produce sinusoidal variation in the capacitance. The generated ac current through the resistance R is rectified and read by a moving coil instrument an amplifier is needed, if the shunt capacitance is large or longer leads are used for connection to rectifier and meter. The instrument is calibrated using a potential divider or sphere gap. The meter scale is linear and its range can be extended by extrapolation.



Advantages of Generating Voltmeters

(i) No source loading by the meter,

(ii) no direct connection to high voltage electrode,

(iii) scale is linear and extension of range is easy, and

(iv) a very convenient instrument for electrostatic devices such as Van de Graaff generator and particle accelerators.

Limitations of Generating Voltmeters

(i) They require calibration,

(ii) careful construction is needed and is a cumbersome instrument requiring an auxiliary drive, and

(iii) disturbance in position and mounting of the electrodes make the calibration invalid.

Oscillating Spheroid

The period of oscillation of an oscillating spheroid in a uniform electric field is proportional to the applied electric field. This principle is made use of in measuring high dc voltages. The period of oscillation of a suspended spheroid between two electrodes with and without an electric field present is measured. If the frequency of the oscillation for small amplitudes is f and f_0 respectively, then the electric field

$$E \propto (f^2 - {f_o}^2)^{1/2}$$

and hence the applied voltage

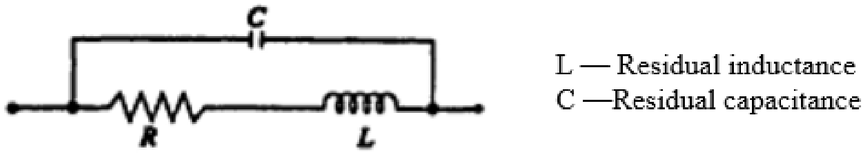
$$V \propto (f^2 - {f_o}^2)^{1/2}$$

since $E=V/d$ (d being the gap separation between the electrodes). The proportionality constant can be determined from the dimensions of the spheroid or experimentally.

Measurement of High AC Voltages

Series Impedance Voltmeters

For power frequency ac measurements, the series impedance may be a pure resistance or a reactance. Since resistances involve power losses, often a capacitor is preferred as a series reactance. Moreover, for high resistances, the variation of resistance with temperature is a problem, and the residual inductance of the resistance gives rise to an impedance different from its ohmic resistance. High resistance units for high voltages have stray capacitances and hence a unit resistance will have an equivalent circuit as shown in figure below.



Simplified lumped parameter equivalent circuit of a high ohmic resistance R

At any frequency ω of the ac voltage, the impedance of the resistance R is;

$Z = \frac{R+j\omega L}{(1-\omega^2 LC)+j\omega RC}$ and the total phase angle is $\tan\varphi = (\frac{\omega L}{R} - \omega RC)$. This can be made zero and independent of frequency, if $\frac{L}{C} = R^2$

For extended and large dimensioned resistors, this equivalent circuit is not valid and each elemental resistor has to be approximated with this equivalent circuit. The entire resistor unit then has to be taken as a transmission line equivalent, for calculating the effective resistance. Also, the ground or stray capacitance of each element influences the current flowing in the unit, and the indication of the meter results in an error. The equivalent circuit of a high voltage resistor neglecting inductance and the circuit of compensated series resistor using guard and timing resistors is shown in Figs. a and b respectively. Stray ground capacitance effects can be removed by shielding the resistor R by a second surrounding spiral R_s, which shunts the actual resistor but does not contribute to the current through the instrument. By tuning the resistors R_a, the shielding resistor end potentials may be adjusted with respect to the actual measuring resistor so that the resulting compensation currents between the shield and the measuring resistors provide a minimum phase angle.

Series Capacitance Voltmeter

To avoid the drawbacks pointed out earlier, a series capacitor is used instead of a resistor for ac high voltage measurements.

The current I_c through the meter is $I_C = j\omega CV$

where, C = capacitance of the series capacitor, ω = angular frequency, and V= applied ac voltage.

If the ac voltage contains harmonics, error due to changes in series impedance occurs. The rms value of the voltage V with harmonics is given by

$$V = \sqrt{{V_1}^2 + {V_2}^2 + \cdots \ldots \ldots . + {V_n}^2}$$

where V_1, V_2 ... V_n represent the rms value of the fundamental, second... and nth harmonics. The currents due to these harmonics are

$$I_1 = \omega C V_1$$

$$I_2 = 2\omega C V_2 \text{ , ……….. ,}$$

$$I_n = n\omega C V_n$$

Hence, the resultant rms current is $I = \omega C\,({V_1}^2 + 4{V_2}^2 + \cdots \ldots + n^2{V_n}^2)^{1/2}$

With a 10% fifth harmonic only, the current is 11.2% higher, and hence the error is 11.2% in the voltage measurement This method is not recommended when ac voltages are not pure sinusoidal waves but contain considerable harmonics. Series capacitance voltmeters were used with cascade transformers for measuring rms values up to 1000 kV. The series capacitance was formed as a parallel plate capacitor between the high voltage terminal of the transformer and a ground plate suspended above it. A rectifier ammeter was used as an indicating instrument and was directly calibrated in high voltage rms value. The meter was usually a 0-100 µA moving coil meter and the over all error was about 2%.

Capacitance Potential Dividers and Capacitance Voltage Transformers

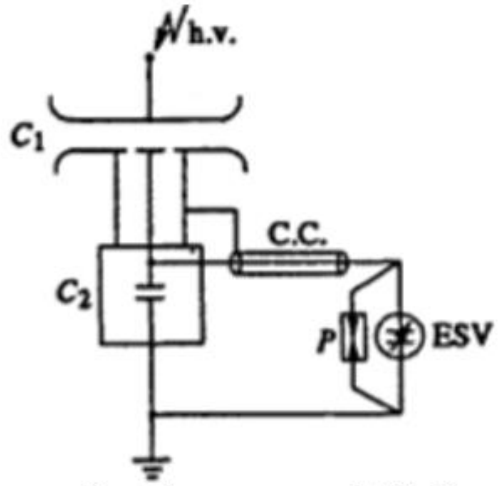
The errors due to harmonic voltages can be eliminated by the use of capacitive voltage dividers with an electrostatic voltmeter or a high impedance meter such as a V.T.V.M. If the meter is connected through a long cable, its capacitance has to be taken into account in calibration. Usually, a standard compressed air or gas condenser is used as C_1, and C_2 may be any large capacitor (mica, paper, or any low loss condenser). C_1 is a three terminal capacitor and is connected to C_2 through a shielded cable, and C_2 is completely shielded in a box to avoid stray capacitances. The applied voltage V_1 is given by;

$$V_1 = V_2\left(\frac{C_1 + C_2 + C_m}{C_1}\right)$$

Where C_m is the capacitance of the meter and the connecting cable and the leads and V_2 is the meter reading.

VTVM=vacuum tube voltmeter

CVT= Capacitance Voltage Transformer



Capacitance potential divider

C_1 — Standard compressed gas h.v. condenser
C_2 — Standard low voltage condenser
ESV — Electrostatic voltmeter
P — Protective gap
C.C. — Connecting cable

Capacitance Voltage Transformer—CVT

Capacitance divider with a suitable matching or isolating potential transformer tuned for resonance condition is often used in power systems for voltage measurements. This is often referred to as CVT. In contrast to simple capacitance divider which requires a high impedance meter like a V.T.V.M. or an electrostatic voltmeter, a CVT can be connected to a low impedance device like a wattmeter pressure coil or a relay coil. CVT can supply a load of a few VA.

C_1 is made of a few units of high voltage condensers, and the total capacitance will be around a few thousand picofarads as against a gas filled standard condenser of about 100 pF. A matching transformer is connected between the load or meter M and C_2. The transformer ratio is chosen on economic grounds, and the h.v. winding rating may be 10 to 30 kV with the LV winding rated from 100 to 500 V. The value of the tuning choke L is chosen to make the equivalent circuit of the CVT purely resistive or to bring resonance condition. This condition is satisfied when

$\omega(L + L_T) = \frac{1}{\omega(C_1+C_2)}$ where, L= inductance of the choke, and L_T = equivalent inductance of the transformer referred to hv side.

The voltage V_2 (meter voltage) will be in phase with the input voltage V_1. The phasor diagram of CVT under resonant conditions is shown in figure below. The meter is taken as a resistive load, and X_m' is neglected. The voltage across the load referred to the divider side will be $V_2' = (I_m'R_m')$ and $Vc_2 = V_2' + I_m(R_e + X_e)$. It is clear from the phasor diagram that V_1 (input voltage) = $(Vc_1 + Vc_2)$ and is in phase with V_2', the voltage across the meter. R_e and X_e include the potential transformer resistance and leakage reactance. Under this condition, the voltage ratio becomes;

$$\alpha = \frac{V_1}{V_2} = \frac{V_{C1}+V_{Ri}+V_2}{V_2}$$

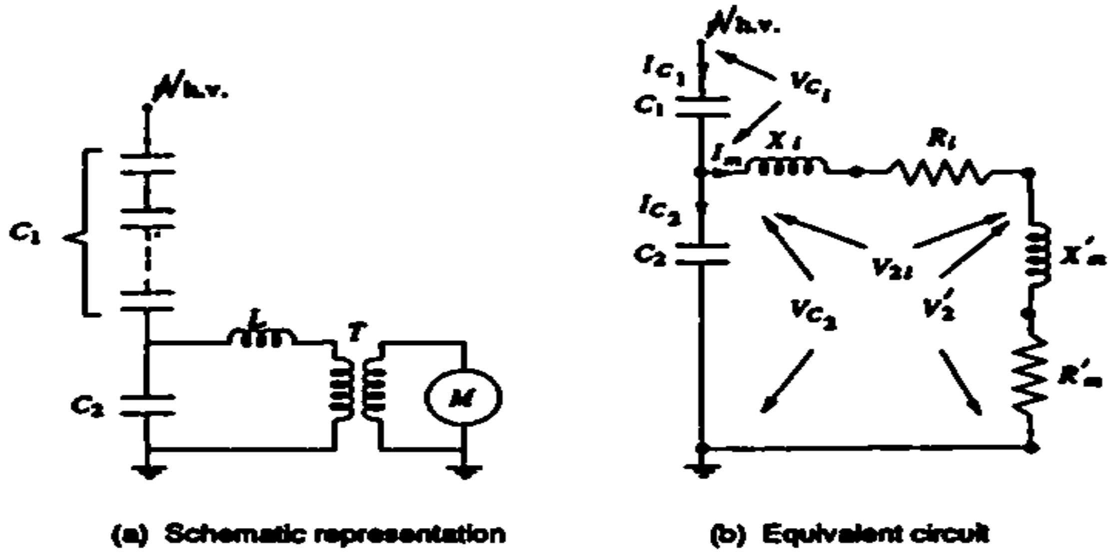


Fig: Capacitive Voltage Transformer (CVT)

neglecting the voltage drop I_m . X_e which is very small compared to the voltage Kc_1) where V_{Ri} is the voltage drop in the transformer and choke windings.

The advantages of a CVT are:

(i) simple design and easy installation,

(ii) can be used both as a voltage measuring device for meter and relaying purposes and also as a coupling condenser for power line carrier communication and relaying.

(iii) frequency independent voltage distribution along elements as against conventional magnetic potential transformers which require additional insulation design against surges, and

(iv) provides isolation between the high voltage terminal and low voltage metering.

The disadvantages of a CVT are:

(i) the voltage ratio is susceptible to temperature variations, and

(ii) the problem of inducing ferro-resonance in power systems.

Potential Transformers (Electro-magnetic Type)

Magnetic potential transformers are the oldest devices for ac measurements. They are simple in construction and can be designed for any voltage. For very high voltages, cascading of the transformers is possible. The voltage ratio is

$$\frac{V_1}{V_2} = \alpha = \frac{N_1}{N_2}$$

where V_1 and V_2 are the primary and secondary voltages, and N_1 and N_2 are the respective turns in the windings.

These devices suffer from the ratio and phase angle errors caused by the magnetizing and leakage impedances of the transformer windings. The errors are compensated by adjusting the turns ratio with the tapping's on the high voltage side under load conditions. Potential transformers (PT) do not permit fast rising transient or high frequency voltages along with the normal supply frequency, but harmonic voltages are usually measured with sufficient accuracy. With high voltage testing transformers, no separate potential transformer is used, but a PT winding is incorporated with the high voltage windings of the testing transformer.

With test objects like insulators, cables, etc. which are capacitive in nature, a voltage rise occurs on load with the testing transformer, and the potential transformer winding gives voltage values less than the actual voltages applied to the test object If the percentage impedance of the testing transformer is known, the following correction can be applied to the voltage measured by the PT winding of the transformer.

$$V_2 = V_{20}(1 + 0.01V_x C/C_N)$$

Where, V_{20} = open circuit voltage of the PT winding

C_N = load capacitance used for testing

C = test object capacitance (C≪ C_N) and

V_x = % reactance drops in the transformer

Electrostatic Voltmeters

Principle: In electrostatic fields, the attractive force between the electrodes of a parallel plate capacitor is given by;

$$F = \left|-\frac{\delta W_s}{ds}\right| = \left|\frac{\delta}{\delta s}\left(\frac{1}{2}CV^2\right)\right| = \left|\frac{1}{2}V^2\frac{\delta C}{\delta s}\right|$$

$$= \frac{1}{2}\in_0 V^2\frac{A}{S^2} = \frac{1}{2}\in_0 A\left(\frac{V}{S}\right)^2 = \frac{d^2}{2825}\left(\frac{V}{S}\right)^2 \; gm.wt$$

Where, V = applied voltage between plates

C = Capacitance between the plates

A = area of cross-section of the plates

d = diameter of plates

s = separation between the plates

$\in_0$ = permittivity of the medium (air or free space)

W_s = work done in displacing a plate

When one of the electrodes is free to move, the force on the plate can be measured by controlling it by a spring or balancing it with a counterweight. For high voltage measurements, a small displacement of one of the electrodes by a fraction of a millimeter to a few millimeters is usually sufficient for voltage measurements. As the force is proportional to the square of the applied voltage, the measurement can be made for ac or dc voltages.

Construction: Electrostatic voltmeters are made with parallel plate configuration using guard rings to avoid corona and field fringing at the edges. An absolute voltmeter is made by balancing the plate with a counter weight and is calibrated in terms of a small weight. Usually the electrostatic voltmeters have a small capacitance (5 to 50 pF) and high insulation resistance ($R \geq 10^{13}\ \Omega$). Hence, they are considered as devices with high input impedance. The upper frequency limit for ac applications is determined from the following considerations:

(i) natural frequency of the moving system,

(ii) resonant frequency of the load and stray inductances with meter capacitance, and

(iii) the R-C behavior of the retaining or control spring (due to the frictional resistance and elastance).

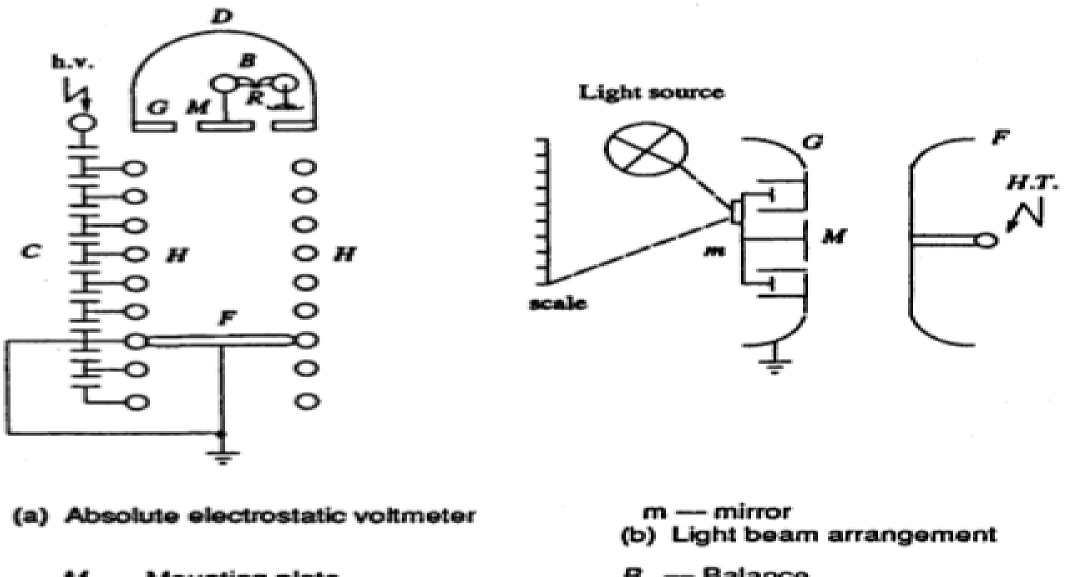
An upper frequency limit of about one MHz is achieved in careful designs. The accuracy for ac voltage measurements is better than ±0.25%, and for dc voltage measurements it may be ±0.1% or less.

Schematic diagram

It consists of parallel plane disc type electrodes separated by a small distance. The moving electrode is surrounded by a fixed guard ring to make the field uniform in the central region. In order to measure the given voltage with precision, the disc diameter is to be increased, and the gap distance is to be made less. The limitation on the gap distance is the safe working stress (V/s) allowed in air which is normally 5 kV/cm or less. Several forms of voltmeters differ in the manner of obtaining the restoring force. For conventional versions of meters, a simple spring control is used, which actuates a pointer to move on the scale of the instruments. In more versatile instruments, only small movements of the moving electrodes are allowed, and the movement is amplified through optical means (lamp and scale arrangement as used with moving coil galvanometers). Two air vane dampers are used to reduce vibrational tendencies in the moving system, and the elongation of the spring is kept minimum to avoid field disturbances. The range of the instrument is easily changed by changing the gap separation so that V/s or electric stress is the same for the maximum value in any range. Multi-range instruments are constructed for 600 kV rms and above.

Constructional details

The control torque is provided by a balancing weight. The moving disc M forms the central core of the guard ring G which is of the same diameter as the fixed plate F. The cap D encloses a sensitive balance B, one arm of which carries the suspension of the moving disc. The balance beam carries a mirror which reflects a beam of light. The movement of the disc is thereby magnified. As the spacing between the two electrodes is large, the uniformity of the electric field is maintained by the guard rings H which surround the space between the discs F and M. The guard rings H are maintained at a constant potential in space by a capacitance divider ensuring a uniform special potential distribution.



(a) Absolute electrostatic voltmeter

m — mirror
(b) Light beam arrangement

M — Mounting plate
G — Guard plate
F — Fixed plate
H — Guard hoops or rings

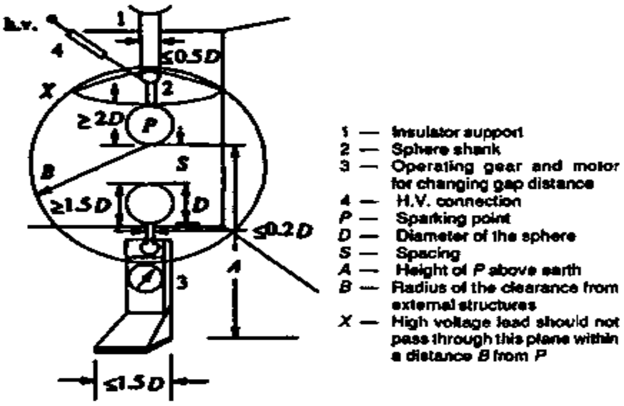
B — Balance
C — Capacitance divider
D — Dome
R — Balancing weight

Spark Gaps

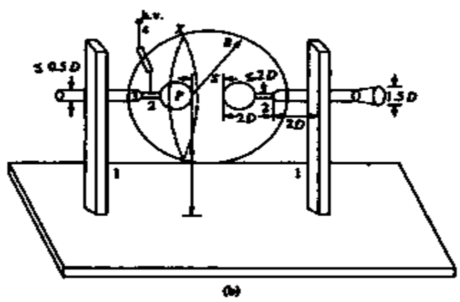
A uniform field spark gap will always have a sparkover voltage within a known tolerance under constant atmospheric conditions. Hence a spark gap can be used for measurement of the peak value of the voltage, if the gap distance is known. Normally, only sphere gaps are used for voltage measurements. In certain case uniform field gaps and rod gaps are also used, but their accuracy is less. The spark gap breakdown, especially the sphere gap breakdown, is independent of the voltage waveform and hence is highly suitable for all types of waveforms from dc to impulse voltages of short rise times (rise time ≥ 0.5 µs). As such, sphere gaps can be used for radio frequency ac voltage peak measurements also (up to 1 MHz).

Sphere Gap Measurements

Sphere gaps are arranged either (i) vertically with lower sphere grounded, or (ii) horizontally with both spheres connected to the source voltage or one sphere grounded. In horizontal configurations, both spheres are symmetrically at high voltage above the ground. The two spheres used are identical in size and shape.



(a) Vertical arrangement of sphere gap



Horizontal arrangement of sphere gap

The voltage to be measured is applied between the two spheres and the distance or spacing S between them gives a measure of the sparkover voltage. A series resistance is usually connected between the source and the sphere gap to (i) limit the breakdown current, and (ii) to suppress unwanted oscillations in the source voltage when breakdown occurs (in case of impulse voltages). The value of the series resistance may vary from 100 to 1000 k Ω for ac or dc voltages and not more than 500 Ω in the case of impulse voltages.

In the case of ac peak value and dc voltage measurements, the applied voltage is uniformly increased until sparkover occurs in the gap. Generally, a mean of about five breakdown values is taken when they agree to within ±3%. In the case of impulse voltages, to obtain 50% flashover voltage, two voltage limits, differing by not more than 2% are set such that on application of lower limit value either 2 or 4 flashovers take place and on application of upper limit value 8 or 6 flashovers take place respectively. The mean of these two limits is taken as 50% flashover voltage. In any case, a preliminary sparkover voltage measurement is to be made before actual measurements are made.

Measurement of Impulses

Potential Divider with a Cathode Ray Oscillograph

Potential or voltage dividers for high voltage impulse 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. A schematic diagram of a potential divider with its terminating equipment is given in figure. Z_1 is usually a resistor in case of a resistance potential divider, or a capacitor 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. 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.

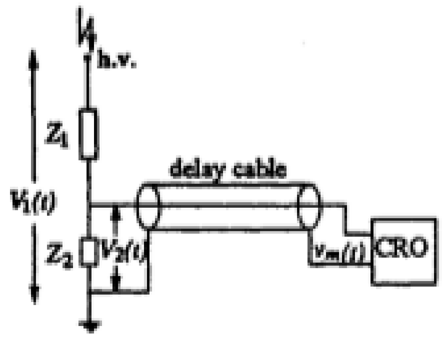
When a step or fast rising voltage is applied at the high voltage terminal, the voltage developed across the element Z_2 will not have the true waveform as that of the applied voltage. The cable can also introduce distortion in the waveshape. The following elements mainly constitute the different errors in the measurement:

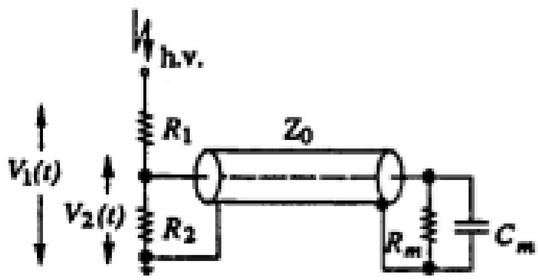
(i) residual inductance in the elements;

(ii) stray capacitance occurring (a) between the elements, (b) from sections and terminals of the elements to ground, and (c) from the high voltage lead to the elements or sections;

(iii) the impedance errors due to connecting leads

(iv) parasitic oscillations due to lead and cable inductances and capacitance of high voltage terminal to ground.



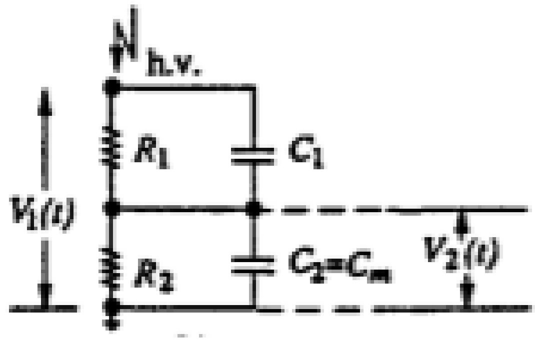


$\alpha = \frac{V_1(t)}{V_2(t)} = 1 + \frac{R_1}{R_2}$

But as R_2 is connected through the cable to the oscilloscope, the relation not exactly as shown above.

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

So a compensated circuit is used.



Capacitance Voltage Divider

Capacitance C_1 is formed between the hv terminal of the source (impulse generator) and that of the test object or any other point of measurement. The CRO is located within the shielded screen surrounding capacitance C_2. C_2 includes the capacitance used, the lead capacitance, input capacitance of the CRO, and other ground capacitances. The advantage of this connection is that the loading on the source is negligible; but a small disturbance in the location of C_2 or hv electrode or the presence of any stray object nearby changes the capacitance C_1, and hence the divider ratio is affected.

The ratio of the divider $\alpha = \frac{V_1(t)}{V_2(t)} = 1 + \frac{C_2}{C_1}$

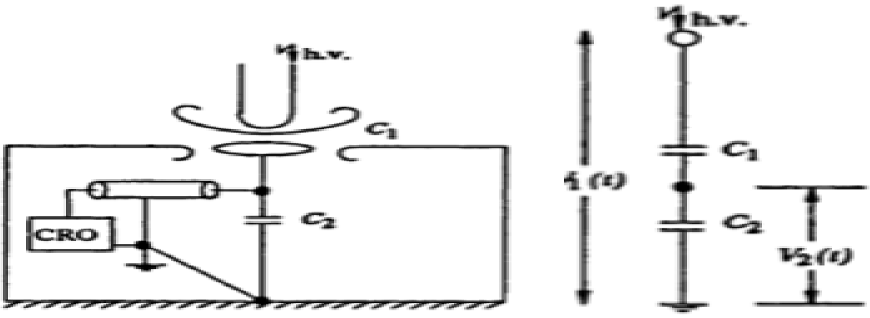
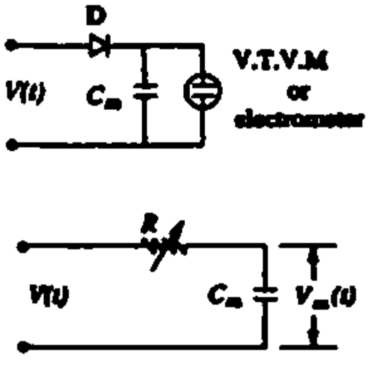


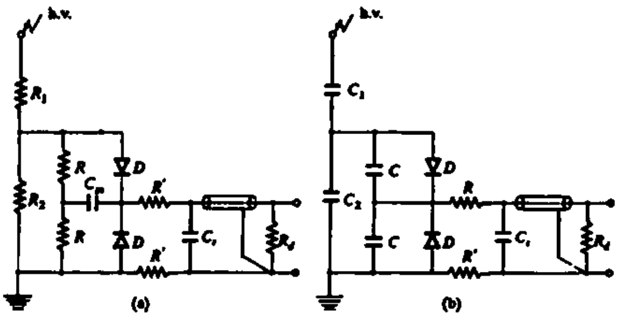
Fig: Capacitance voltage divider for very high voltage and electrical equivalent circuit

Peak Voltmeters

Sometimes it is enough if the peak value of an impulse voltage wave is measured; its waveshape might already be known or fixed by the source itself. This is highly useful in routine impulse testing work. The instrument is normally connected to the low voltage arms of the potential dividers. Diode D conducts for positive voltages only. For negative pulses, the diode has to be connected in reverse. When a voltage impulse v(t) appears across the low voltage arm of the potential divider, the capacitor C_m is charged to the peak value of the pulse. When the amplitude of the signal starts decreasing the diode becomes reverse biased and prevents the discharging of the capacitor C_m. The voltage developed across Cm is measured by a high impedance voltmeter (an electrostatic voltmeter or an electrometer).



Basic and equivalent circuits



Peak reading voltmeter for either polarity with (a) resistance divider, and (b) capacitance divider

Klydonograph or Surge Recorder

Since lightning surges are infrequent and random in nature, it is necessary to instal a large number of recording devices to obtain a reasonable amount of data regarding these surges produced on transmission lines and other equipments. Some fairly simple devices have been developed for this purpose. Klydonograph is one such device which makes use of the patterns known as Litchenberg figures which are produced on a photographic film by surface corona discharges.

The Klydonograph (Fig. 4.24) consists of a rounded electrode resting upon the emulsion side of a photographic film or plate which is kept on the smooth surface of an insulating material plate backed by a plate electrode. The minimum critical voltage to produce a figure is about 2 kV and the maximum voltage that can be recorded is about 20 kV, as at higher voltages spark overs occurs which spoils the film. The device can be used with a potential divider to measure higher voltages and with a resistance shunt to measure impulse current.

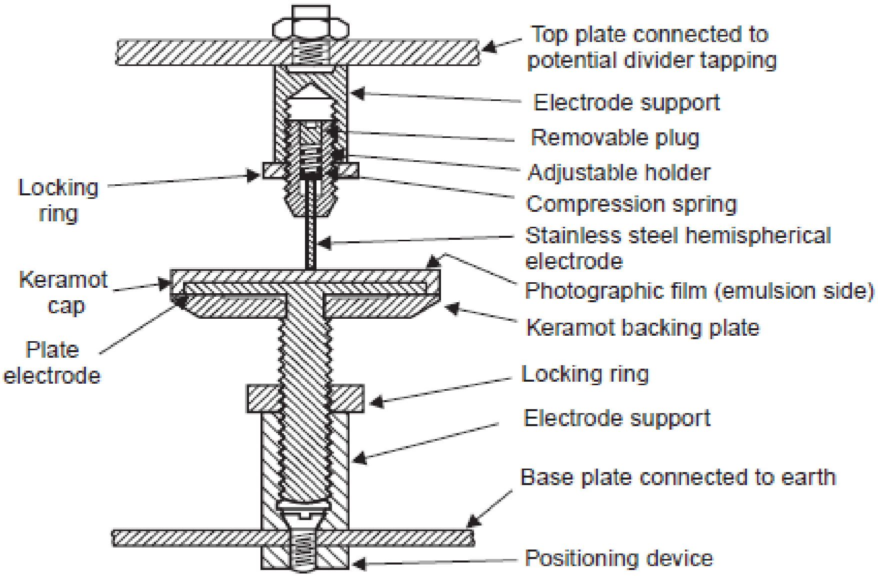


Fig. 4.24 Klydonograph

There are characteristic differences between the figures for positive and negative voltages. However, for either polarity the radius of the figure (if it is symmetrical) or the maximum distance from the centre of the figure to its outside edge (if it is unsymmetrical) is a function only of the applied voltage. The oscillatory voltages produce superimposed effects for each part of the wave. Thus it is possible to know whether the wave is unidirectional or oscillatory. Since the size of the figure for positive polarity is larger, it is preferable to use positive polarity figures. This is particularly desirable in case of measurement of surges on transmission lines or other such equipment which are ordinarily operating on a.c. voltage and the alternating voltage gives a black band along the centre of the film caused by superposition of positive and negative figures produced on each half cycle. For each surge voltage it is possible to obtain both positive and negative polarity figures by connecting pairs of electrodes in parallel, one pair with a high voltage point and an earthed plate and the other pair with a high voltage plate and an earthed point.

Klydonograph being a simple and inexpensive device, a large number of elements can be used for measurement. It has been used in the past quite extensively for providing statistical data on magnitude, polarity and frequency of voltage surges on transmission lines even though its accuracy of measurement is only of the order of 25 per cent.

Measurement of high dc current and impulse current

High currents are used in power system for testing circuit breakers, cables lightning arresters etc. and high currents are encountered during lightning discharges, switching transients and shunt faults. These currents require special techniques for their measurements.

Hall Generator

Hall effect (Fig. 4.25) is used to measure very high direct current. Whenever electric current flows through a metal plate placed in a magnetic field perpendicular to it, Lorenz force will deflect the electrons in the metal structure in a direction perpendicular to the direction of both the magnetic field and the flow of current. The charge displacement results in an e.m.f. in the perpendicular direction called the Hall voltage. The Hall voltage is proportional to the current I, the magnetic flux density B and inversely proportional to the plate thickness d *i.e.*,

$$V_H = R\frac{BI}{d}$$

where R is the Hall coefficient which depends upon the material of the plate and temperature of the plate. For metals the Hall coefficient is very small and hence semiconductor materials are used for which the Hall coefficient is high.

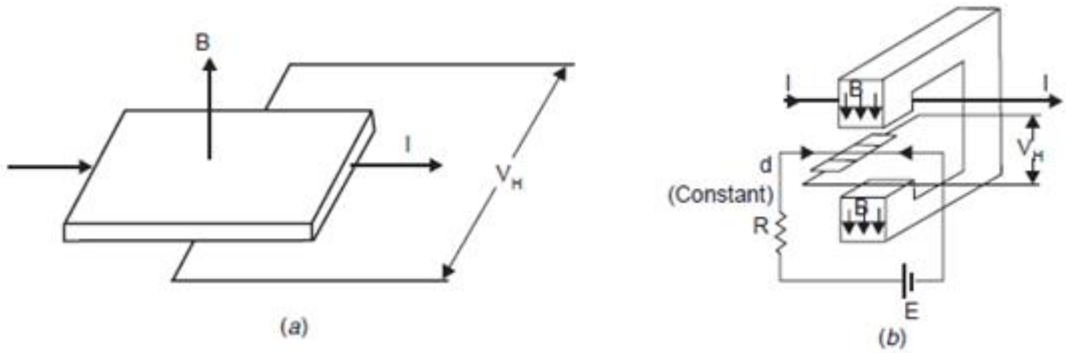


Fig. 4.25 Hall generator

When large d.c. currents are to be measured the current carrying conductor is passed through an iron cored magnetic circuit (Fig. 4.25 (*b*)). The magnetic field intensity produced by the conductor in the air gap at a depth d is given by

$$H = \frac{1}{2\,\pi\, d}$$

The Hall element is placed in the air gap and a small constant d.c. current is passed through the element. The voltage developed across the Hall element is measured and by using the expression for Hall voltage the flux density B is calculated and hence the value of current I is obtained.

Magnetic Potentiometer or Rogowaki coil

If the current to be measured is flowing through a conductor which is surrounded by a coil as shown in Fig. 4.29, and M is the mutual inductance between the coil and the conductor, the voltage across the coil terminals will be:

$$v(t) = M\frac{di}{dt}$$

Usually the coil is wound on a non-magnetic former in the form of a toroid and has a large number of turns, to have sufficient voltage induced which could be recorded. The coil is wound criss-cross to reduce the leakage inductance. If M is the number of turns of the coil, A the coil area and l_m its mean length, the mutual inductance is given by

$$M = \frac{\mu_0 NA}{l}$$

Usually an integrating circuit RC is employed as shown in Fig. 4.29 to obtain the output voltage proportional to the current to be measured. The output voltage is given by

$$v_0(t) = \frac{1}{RC}\int_0^t v(t)dt = \frac{1}{RC}\int M\frac{di}{dt}.dt = \frac{M}{RC}\int di = \frac{M}{RC}i(t)$$

or $$v(t) = \frac{RC}{M}v_0(t)$$

Integration of $v(t)$ can be carried out more elegantly by using an appropriately wired operational amplifier. The frequency response of the Rogowski coil is flat upto 100 MHz but beyond that it is affected by the stray electric and magnetic fields and also by the skin effect.

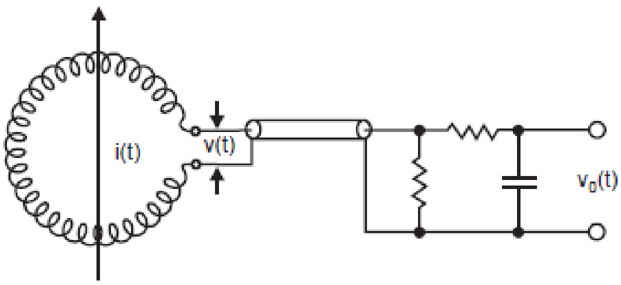


Fig. 4.29 Rogowski coil for high impulse current measurements

Magnetic Links

These are used for the measurement of peak magnitude of the current flowing in a conductor. These links consist of a small number of short steel strips on high retentivity. The link is mounted at a known distance from the current carrying conductor. It has been found through experiments that the remanant magnetism of the link after impulse current of 0.5/5 micro sec shape passes through the conductor is same as that caused by a direct current of the same peak value. Measurement of the remanance possessed by the link after the impulse current has passed through the conductor enables to calculate the peak value of the current. For accurate measurements, it is usual to mount two or more links at different distances from the same conductor. Because of its relative simplicity, the method has been used for measurement of lightning current especially on transmission towers. It is to be noted that the magnetic links help in recording the peak value of the impulse current but gives no information regarding the wave shape of the current. For this purpose, an instrument
called Fulcronograph has been developed which consists of an aluminium wheel round the rim of which are slots containing magnetic links of sufficient length to project on both sides of the wheel. As the

wheel is rotated, the links pass successively through a pair of narrow coils through which flows the current to be measured. The current at the instant during which a particular link traverses the coil, can be determined by a subsequent measurement of the residual flux in the link and, therefore, a curve relating the variation of current with time can be obtained. The time scale is governed by the speed of rotation of the wheel.

UNIT 3 INTRODUCTION TO HIGH VOLTAGE TESTING

Electrical equipment must be capable of withstanding over-voltages during operation. Thus, by suitable testing procedure we must ensure that this is done. High voltage testing can be broadly classified into **testing of insulating materials** (samples of dielectrics) and **tests on completed equipment**.

The tests carried out on samples of dielectric consist generally of the measurement of permittivity, dielectric loss per unit volume, and the dielectric strength of the material. The first two can be measured using the High Voltage Schering Bridge.

The tests carried out on completed equipment are the measurement of capacitance, the power factor or the total dielectric loss, the ultimate breakdown voltage and the flash-over voltage. The breakdown voltage tests on completed equipment is only done on a few samples since it permanently damages and destroys the equipment from further use. However, since all equipment have to stand up to a certain voltage without damage under operating conditions, all equipment is subjected to withstand tests on which the voltage applied is about twice the normal voltage, but which is less than the breakdown voltage.

General Tests Carried Out on High Voltage Equipment

Sustained low-frequency tests

Sustained low frequency tests are done at power frequency (50 Hz) and are the commonest of all tests. These tests are made upon specimens of insulation materials for the determination of dielectric strength and dielectric loss, for routine testing of supply mains, and for work tests on high voltage transformers, insulators and other apparatus. Since, the dielectric loss is sensitive to electric stress, the tests are carried out at the highest ultimate stress possible. For testing of insulators and in high tension cables, voltages as high as 2000 kV may be used.

High voltage a.c. tests at 50 Hz are carried out as Routine tests on low voltage (230 or 400 V) equipment. Each one of these devices are subjected to a high voltage of 1 kV + 2 × (working voltage). A 230 V piece of equipment may thus be subjected to about 1.5 to 2 kV. These tests are generally carried out after manufacture before installation. The high voltage is applied across the device under test by means of a transformer. The transformer need not have a high-power rating. If a very high voltage is required, the transformer is usually build up in stages by cascading. Also, the insulation bushing may be reduced in size. The transformers are usually designed to have poor regulation so that if the device under test is faulty and breakdown occurs, the terminal voltage would drop due to the high current caused. A resistance of about 1 ohm/volt is used in series with the transformer so as to limit the current in the event of a breakdown to about 1 A.

In all high voltage tests, safety precautions are taken so as to ensure that there is no access to the testing area when the high voltage is on. There would be switches that would automatically be operated when the door to the area is opened etc.

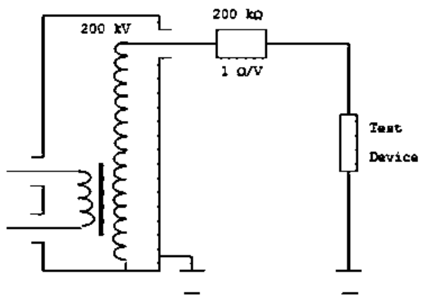


Fig: AC generation test circuit

High Voltage direct current tests

These tests are done on apparatus expected to operate under direct voltage conditions, and also where, due to the inconvenience of the use of high capacity transformers required for extra high tension alternating voltage tests and due to transport difficulties, alternating voltage tests cannot be performed after installation.

A special feature of importance of the dc test is the testing of cables which are expected to operate under ac conditions. If the tests are done under ac conditions, a high charging current would be drawn and the transformer used would have to have a high current rating. It is thus normal to subject the cable (soon after laying it, but before energizing it) to carry out a high voltage test under dc conditions. The test voltage would be about 2× (working voltage) and the voltage is maintained from 15 min to 1.5 hrs. This dc test is not complete equivalent to the corresponding ac conditions, it is the leakage resistance which would determine the voltage distribution, while in the ac conditions, it is the layers of different dielectrics that determine the voltage distribution in the cable. Although the electric field differs in the 2 cases, it is likely that the cable will stand up to the required ac voltage.

High-frequency tests

High frequency tests at frequencies varying from several kHz are important where there is a possibility of high voltage in the lines etc., and in insulators which are expected to carry high frequency such as radio transmitting stations. Also, in the case of porcelain insulators, breakdown or flashover occurs in most cases as a result of high frequency disturbances in the line caused by either switching operations or external causes. Also, high frequency oscillations cause failure of insulation at a comparatively low voltage due to high dielectric loss and heating.

High voltage tests at high frequency are made at the manufacturing works so as to obtain a design of insulator which will satisfactorily withstand all conditions of service. In the case of power line suspension insulators, it is possible that breakdown or flash over would occur due to high frequency over voltages produced by faults or switching operations in the line. Sudden interruptions in the line would give rise to voltage waves in the line of high frequency. These might cause flashover of the insulators.

The behavior of insulating materials at high frequencies are quite different to that at ordinary power frequency. The dielectric loss per cycle is very nearly constant so that at high frequencies the dielectric loss is much higher and the higher loss causes heating effects. The movements of charge carriers would be different. At high frequency the polarity of electrodes might have changed before the charge carriers have travelled from one electrode to the other, so that they may go about half-way and turn back.

There are two kind of high frequency tests carried out. These are-

(a) Tests with apparatus which produces undamped high-frequency oscillations: Undamped oscillations do not occur in power systems but are useful for insulation testing purposes especially for insulation to be in radio work.

(b) Tests with apparatus producing damped high-frequency oscillations: When faults to earth or sudden switching of transmission lines occur, high frequency transients occur whose frequency depends on the capacitance and inductance of the line and will be about 50 KHz to about 200 KHz. These are damped out with time.

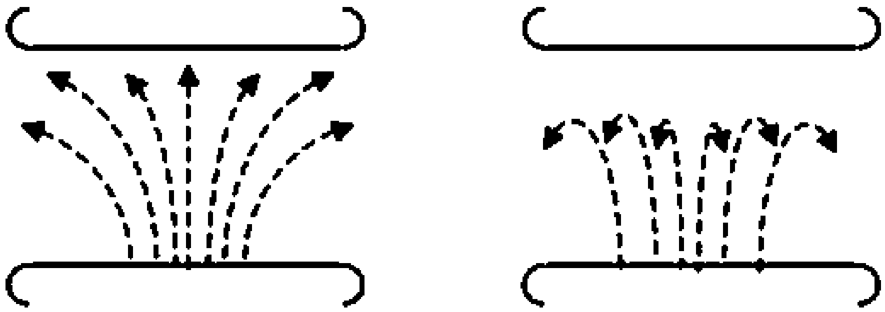


Fig: Movement of charge carriers

Surge or impulse tests

These tests are carried out in order to investigate the influence of surges in transmission lines, breakdown of insulators and of the end turns of transformer connections to line. In impulse testing, to represent surges generated due to lightning, the IEC Standard impulse wave of 1.2/50 µs wave is generally used. By the use of spark gaps, conditions occurring on the flash over to line are simulated. The total duration of a single lightning strike is about 100 µs, although the total duration of the lightning stroke may be a few seconds.

Over-voltages of much higher duration also arise due to line faults, switching operations etc, for which impulse waves such as 100/5000 µs duration may be used. In surge tests it is required to apply to the circuit or apparatus under test, a high direct voltage whose value rises from zero to maximum in a very short time and dies away again comparatively slowly.

While impulse and high frequency tests are carried out by manufacturers, in order to ensure that their finished products will give satisfactory performance in service, the most general tests upon insulating materials are carried out at power frequencies.

Flash-over tests

Porcelain insulators are designed so that spark over occurs at a lower voltage than puncture, thus safeguarding the insulators, in service against destruction in the case of line disturbances. Flash over tests are very importance in this case. The flashover is due to a breakdown of air at the insulator surface and is independent of the material of the insulator. As the flash over under wet conditions and dry condition differ, tests such as the one-minute dry flash over test and the one wet flash over test are performed.

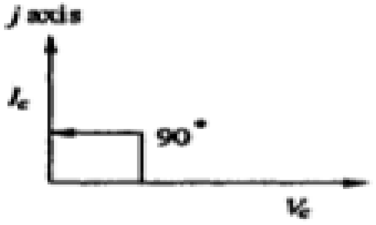
Non-destructive Testing of Insulations

Leakage Current and Dielectric Loss

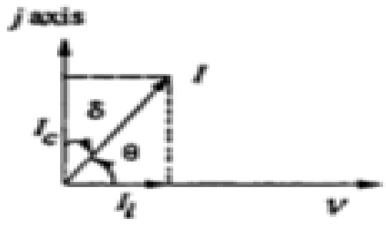
Many insulating substances have dielectric constant greater than unity and have dielectric loss when subjected to ac voltages. These two quantities, namely, the dielectric constant and the loss depend on the magnitude of the voltage stress and on the frequency of the applied voltage. When a dielectric is used in an electrical equipment such as a cable or a capacitor, the variation of these quantities with frequency is of importance. The microscopic properties of the dielectric are described by combining the variation of the above two quantities into one "complex quantity" known as "complex permittivity" and determining them at various frequencies.

A capacitor connected to a sinusoidal voltage source $v = v_o \exp(j\omega t)$ with an angular frequency $\omega = 2\pi f$ stores a charge q = C_0V and draws a charging current $I_C = \frac{dq}{dt}$ = j$\omega C_0 V$. When the dielectric is vacuum, C_0 is the vacuum capacitance or geometric capacitance of the condenser and the current leads the voltage by 90°.

Under these conditions, if the same voltage v is applied, there will be a charging current Ic and loss component of the current I_l. I_l will be equal to Gv where G represents the conductance of the dielectric material. The total current $I = I_c + I_l = (j\omega C+G)V$. The current leads the voltage by an angle θ which is less than 90°. The loss angle δ is equal to (90 - θ)°. The phasor diagrams of an ideal capacitor and a capacitor with a lossy dielectric are shown in Figs.



(a) Ideal capacitor



(b) Capacitor with a lossy dielectric

It would be premature to conclude that the dielectric material corresponds to an R-C parallel circuit in electrical behavior. The frequency response of this circuit which can be expressed as the ratio of the loss current to the charging current, i.e. the loss tangent

$$\tan\delta = D = \frac{I_l}{I_C} = \frac{1}{\omega RC}$$

may not at all agree with the result actually observed, because the conductance need not be due to the migration of charges or charge carriers but may represent any other energy consuming process. Hence, it is customary to refer the existence of a loss current in addition to the charging current by introducing complex permittivity.

$$K^* = \varepsilon' - j\varepsilon''$$

So that current I may be written as $I = (j\omega\varepsilon' + \omega\varepsilon'')\frac{C_o}{\varepsilon_o}v = j\omega C_0 K^* v$

Where $K^* = (\varepsilon' - j\varepsilon'')/\varepsilon_0 = K' - jK''$

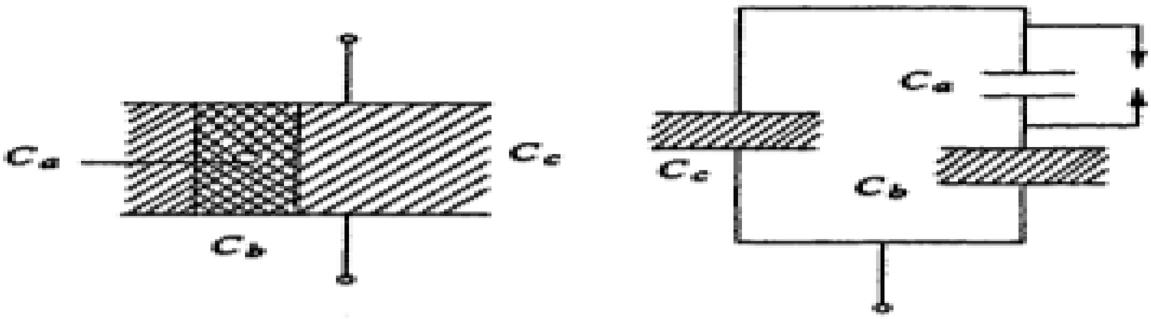
K^* is called the complex relative permittivity or complex dielectric constant, ε' and K' are called the permittivity and relative permittivity and ε'' and K'' are called the loss factor and relative loss factor respectively.

The loss tangent $\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{K''}{K'}$

Partial Discharge

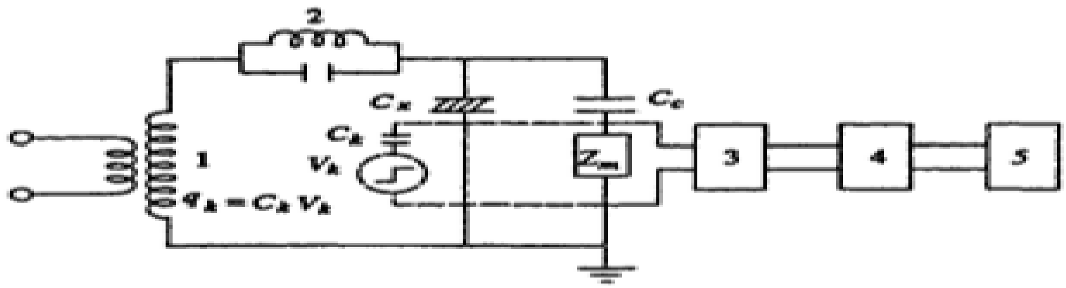
It was found that weak points in an insulation like voids, cracks, and other imperfections lead to internal or intermittent discharges in the insulation. These imperfections being small were not revealed in capacitance measurements but were revealed as power loss components in contributing for an increase 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. If the sites of partial discharges can be located inside an equipment, like in a power cable or a transformer, it gives valuable information to the insulation engineer about the regions of greater stress and imperfections in the fabrication. Based on this information, the designs can be considerably improved.

Consider a capacitor with a void inside the insulation (C_a). The capacitance of the void is represented by a capacitor in series with the rest of the insulation capacitance (C_b). The remaining void-free material is represented by the capacitance Cc. When the voltage across the capacitor is raised, a critical value is reached across the capacitor Ca and a discharge occurs through the capacitor, i.e. it becomes short circuited. This is represented by the closure of the switch.



C_a — Capacitance of the void acting as a spark gap
C_b — Capacitance of the remaining series insulation with the void
C_c — Remaining part of the discharge free insulation of the test object

When Partial Discharge activity occurs within high voltage switchgear insulation, it generates electromagnetic waves in the radio frequency range. Figure gives a simplified circuit for detecting "partial discharges". The high voltage transformer shown is free from internal discharges. A resonant filter is used to prevent any pulses starting from the capacitance of the windings and bushings of the transformer. C_x is the test object, C_c is the coupling capacitor, and Z_m is a detection impedance. The signal developed across the impedance Z_m is passed through a band pass filter and amplifier and displayed on a CRO or counted by a pulse counter multi-channel analyzer unit.



1 — H.V. testing transformer
2 — Filter
3 — Band pass filter
4 — Amplifier
5 — Display unit (CRO or pulse counter or multi-channel analyser unit)

C_x — Sample or test piece
C_c — Coupling condenser
Z_m — Detector impedance
V_k — Calibrating pulse
C_k — Calibrating capacitor
q_k — Calibrator charge

Tests on Insulators

The tests on insulators can be divided into three groups. These are the type tests, sample tests and the routing tests.

Type tests

These tests are done to determine whether the particular design is suitable for the purpose.

(a) Withstand Test: The insulator should be mounted so as to simulate practical conditions. A 1/50 μs wave of the specified voltage (corrected for humidity, air density etc.,) is applied. Flashover or puncture should not occur. [If puncture occurs, the insulator is permanently damaged]. The test is repeated five times for each polarity.

(b) Flash-over test: A 1/50 μs wave is applied. The voltage is gradually increased to the 50% impulse flashover voltage. The test is done for both polarities. There should be no puncture of insulation during these tests.

(c) Dry One-minute test: The insulator, clean and dry, shall be mounted as specified and the prescribed voltage (corrected for ambient conditions) should be gradually brought up (at power frequency) and maintained for one minute. Thee shall not be puncture or flash-over during the test.

Dry flash-over test: The voltage shall then be increased gradually until flash-over occurs. This is repeated ten times. There shall be no damage to the insulator.

(d) One-minute Rain test: The insulator is sprayed throughout the test with artificial rain drawn from a source of supply at a temperature within 10o C of the ambient temperature of the neighborhood of the insulator. The rain is sprayed at an angle of 45° on the insulator at the prescribed rate of 3 mm/minute. The resistivity of the water should be 100 ohm-m ± 10%. The prescribed voltage is maintained for one minute.

Wet flash-over test: The voltage shall then be increased gradually until flash-over occurs. This is repeated ten times. There shall be no damage to the insulator.

(e) Visible discharge test: This states that after the room has been darkened and the specified test voltage applied, after five minutes, there should be no visible signs of corona.

Sample Tests

The sample is tested fully, up to and including the point of breakdown. This is done only on a few samples of the insulator.

(a) Temperature cycle test: The complete test shall consist of five transfers (hot-cold-hot-....), each transfer not exceeding 30 s.

(b) Mechanical loading test: The insulator shall be mechanically loaded up to the point of failure. When failure occurs, the load should not be less than 2000 lbf.

(c) Electro-mechanical test: The insulator is simultaneously subjected to electrical and mechanical stress. (i.e. it shall be subjected to a power frequency voltage and a tensile force simultaneously. The voltage shall be 75% of dry flash-over voltage of the unit. There should be no damage caused.

(d) Overvoltage test: The insulator shall be completely immersed in an insulating medium (oil), to prevent external flashover occurring. The specified overvoltage must be reached without puncture. The voltage is then gradually increased until puncture occurs.

(e) Porosity test: Freshly broken pieces of porcelain shall show no dye penetration after having been immersed for 24 hours in an alcoholic mixture of flushing at a pressure of 2000 p.s.i.

Routine Tests

These are to be applied to all insulators and shall be commenced at a low voltage and shall be increased rapidly until flash-over occurs every few seconds. The voltage shall be maintained at this value for a minimum of five minutes, or if failures occur, for five minutes after the last punctured piece has been removed. At the conclusion of the test the voltage shall be reduced to about one-third of the test voltage before switching off.

Mechanical Routine Test: A mechanical load of 20% in excess of the maximum working load of the insulator is applied after suspending the insulator for one minute. There should be no mechanical failure of the insulator.

Testing of Cables

High voltage power cables have proved quite useful especially in case of HV d.c. transmission. Underground distribution using cables not only adds to the aesthetic looks of a metropolitan city but it provides better environments and more reliable supply to the consumers.

Preparation of Cable Sample

The cable sample has to be carefully prepared for performing various tests especially electrical tests. This is essential to avoid any excessive leakage or end flash overs which otherwise may occur during testing and hence may give wrong information regarding the quality of cables. The length of the sample cable varies between 50 cms to 10 m. The terminations are usually made by shielding the ends of the cable with stress shields so as to relieve the ends from excessive high electrical stresses.

A cable is subjected to following tests:

(*i*) Bending tests.
(*ii*) Loading cycle test.
(*iii*) Thermal stability test.
(*iv*) Dielectric thermal resistance test.
(*v*) Life expectancy test.
(*vi*) Dielectric power factor test.
(*vii*) Power frequency withstand voltage test.
(*viii*) Impulse withstand voltage test.
(*ix*) Partial discharge test.

(*i*) It is to be noted that a voltage test should be made before and after a bending test. The cable is bent round a cylinder of specified diameter to make one complete turn. It is then unwound and rewound in the opposite direction. The cycle is to be repeated three times.

(*ii*) A test loop, consisting of cable and its accessories is subjected to 20 load cycles with a minimum conductor temperature 5°C in excess of the design value and the cable is energized to 1.5 times the working voltage. The cable should not show any sign of damage.

(*iii*) After test as at (*ii*), the cable is energized with a voltage 1.5 times the working voltage for a cable of 132 kV rating (the multiplying factor decreases with increases in operating voltage) and the loading current is so adjusted that the temperature of the core of the cable is 5°C higher than its specified permissible temperature. The current should be maintained at this value for six hours.

(*iv*) The ratio of the temperature difference between the core and sheath of the cable and the heat flow from the cable gives the thermal resistance of the sample of the cable. It should be within the limits specified in the specifications.

(*v*) In order to estimate life of a cable, an accelerated life test is carried out by subjecting the cable to a voltage stress higher than the normal working stress. It has been observed that the relation between the expected life of the cable in hours and the voltage stress is given by

$$g = \frac{K}{n\sqrt{t}}$$

where K is a constant which depends on material and n is the life index depending again on the material.

(*vi*) High Voltage Schering Bridge is used to perform dielectric power factor test on the cable sample. The power factor is measured for different values of voltages *e.g.* 0.5, 1.0, 1.5 and 2.0 times the rated operating voltages. The maximum value of power factor at normal working voltage does not exceed a specified value (usually 0.01) at a series of temperatures ranging from 15°C to 65°C. The difference in the power factor between rated voltage and 1.5 times the rated voltage and the rated voltage and twice the rated voltage does not exceed a specified value. Sometimes the source is not able to supply charging current required by the test cable, a suitable choke in series with the test cable helps in tiding over the situation.

(*vii*) Cables are tested for power frequency a.c. and d.c. voltages. During manufacture the entire cable is passed through a higher voltage test and the rated voltage to check the continuity of the cable. As a routine test the cable is subjected to a voltage 2.5 times the working voltage for 10 min without damaging the insulation of the cable. HV d.c. of 1.8 times the rated d.c. voltage of negative polarity for 30 min. is applied and the cable is said to have withstood the test if no insulation failure takes place.

(*viii*) The test cable is subjected to 10 positive and 10 negative impulse voltage of magnitude as specified in specification, the cable should withstand 5 applications without any damage. Usually, after the impulse test, the power frequency dielectric power factor test is carried out to ensure that no failure occurred during the impulse test.

(*ix*) Partial discharge measurement of cables is very important as it gives an indication of expected life of the cable and it gives location of fault, if any, in the cable.

When a cable is subjected to high voltage and if there is a void in the cable, the void breaks down and a discharge takes place. As a result, there is a sudden dip in voltage in the form of an impulse. This impulse travels along the cable as explained in detail in Chapter VI. The duration between the normal pulse and the discharge pulse is measured on the oscilloscope and this distance gives the location of the void from the test end of the cable. However, the shape of the pulse gives the nature and intensity of the discharge.

In order to scan the entire length of the cable against voids or other imperfections, it is passed through a tube of insulating material filled with distilled water. Four electrodes, two at the end and two in the middle of the tube are arranged. The middle electrodes are located at a stipulated distance and these are energized with high voltage. The two end electrodes and cable conductor are grounded. As the cable is passed between the middle electrode, if a discharge is seen on the oscilloscope, a defect in this part of the cable is stipulated and hence this part of the cable is removed from the rest of the cable.

Testing of Bushing

Bushings are an integral component of high voltage machines. A bushing is used to bring high voltage conductors through the grounded tank or body of the electrical equipment without excessive potential gradients between the conductor and the edge of the hole in the body. The bushing extends into the surface of the oil at one end and the other end is carried above the tank to a height sufficient to prevent breakdown due to surface leakage.

Following tests are carried out on bushings:

(*i*) *Power Factor Test*

The bushing is installed as in service or immersed in oil. The high voltage terminal of the bushing is connected to high voltage terminal of the Schering Bridge and the tank or earth portion of the bushing is connected to the detector of the bridge. The capacitance and p.f. of the bushing is measured at different voltages as specified in the relevant specification and the capacitance and p.f. should be within the range specified.

(*ii*) *Impulse Withstand Test*
The bushing is subjected to impulse waves of either polarity and magnitude as specified in the standard specification. Five consecutive full waves of standard wave form (1/50 sec.) are applied and if two of them cause flash over, the bushing is said to be defective. If only one flash over occurs, ten additional applications are made. If no flash over occurs, bushing is said to have passed the test.

(*iii*) *Chopped Wave and Switching Surge Test*
Chopped wave and switching surge of appropriate duration tests are carried out on high voltage bushings. The procedure is identical to the one given in (*ii*) above.

(*iv*) *Partial Discharge Test*
In order to determine whether there is deterioration or not of the insulation used in the bushing, this test is carried out. The procedure is explained in detail in Chapter-VI. The shape of the discharge is an indication of nature and severity of the defect in the bushing. This is considered to be a routine test for high voltage bushings.

(*v*) *Visible Discharge Test at Power Frequency*
The test is carried out to ascertain whether the given bushing will give rise to ratio interference or not during operation. The test is carried out in a dark room. The voltage as specified is applied to the bushing (IS 2099). No discharge other than that from the grading rings or arcing horns should be visible.

(*vi*) *Power Frequency Flash Over or Puncture Test*
(*Under Oil*): The bushing is either immersed fully in oil or is installed as in-service condition. This test is carried out to ascertain that the internal breakdown strength of the bushing is 15% more than the power frequency momentary dry withstand test value.

Testing of Circuit Breaker

An equipment when designed to certain specification and is fabricated, needs testing for its performance. The general design is tried and the results of such tests conducted on one selected breaker and are thus applicable to all others of identical construction. These tests are called the type tests. These tests are classified as follows:
1. Short circuit tests:
(*i*) Making capacity test.
(*ii*) Breaking capacity test.
(*iii*) Short time current test.
(*iv*) Operating duty test

2. Dielectric tests:
(*i*) Power frequency test:
(*a*) One minute dry withstand test.
(*b*) One minute wet withstand test.
(*ii*) Impulse voltage dry withstand test.

3. Thermal test.

4. Mechanical test

Once a particular design is found satisfactory, a large number of similar C.Bs. are manufactured for marketing. Every piece of C.B. is then tested before putting into service. These tests are known as routine tests. With these tests it is possible to find out if incorrect assembly or inferior quality material has been used for a proven design equipment. These tests are classified as (*i*) operation tests, (*ii*) millivoltdrop tests, (*iii*) power frequency voltage tests at manufacturer's premises, and (*iv*) power frequency voltage tests after erection on site.

Dielectric Tests

The general dielectric characteristics of any circuit breaker or switchgear unit depend upon the basic design *i.e.* clearances, bushing materials, etc. upon correctness and accuracy in assembly and upon the quality of materials used. For a C.B. these factors are checked from the viewpoint of their ability to withstand over voltages at the normal service voltage and abnormal voltages during lightning or other phenomenon.

The test voltage is applied for a period of one minute between (*i*) phases with the breaker closed, (*ii*) phases and earth with C.B. open, and (*iii*) across the terminals with breaker open. With this the breaker must not flash over or puncture. These tests are normally made on indoor switchgear. For such CBs the impulse tests generally are unnecessary because it is not exposed to impulse voltage of a very high order. The high frequency switching surges do occur but the effect of these in cable systems used for indoor switchgear are found to be safely withstood by the switchgear if it has withstood the normal frequency test.

Since the outdoor switchgear is electrically exposed, they will be subjected to over voltages caused by lightning. The effect of these voltages is much more serious than the power frequency voltages in service. Therefore, this class of switchgear is subjected in addition to power frequency tests, the impulse voltage tests.

The test voltage should be a standard 1/50 □□sec wave, the peak value of which is specified according to the rated voltage of the breaker. A higher impulse voltage is specified for non-effectively grounded system than those for solidly grounded system. The test voltages are applied between (*i*) each pole and earth in turn with the breaker closed and remaining phases earthed, and (*ii*) between all terminals on one side of the breaker and all the other terminals earthed, with the breaker open. The specified voltages are withstand values *i.e.* the breaker should not flash over for 10 applications of the wave. Normally, this test is carried out with waves of both the polarities.

The wet dielectric test is used for outdoor switchgear. In this, the external insulation is sprayed for two minutes while the rated service voltage is applied; the test overvoltage is then maintained for 30 seconds during which no flash over should occur. The effect of rain on external insulation is partly beneficial, insofar as the surface is thereby cleaned, but is also harmful if the rain contains impurities.

Thermal Tests

These tests are made to check the thermal behaviour of the breakers. In this test the rated current through all three phases of the switchgear is passed continuously for a period long enough to achieve steady state conditions. Temperature readings are obtained by means of thermocouples whose hot junctions are placed in appropriate positions. The temperature rise above ambient, of conductors, must normally not exceed 40°C when the rated normal current is less than 800 amps and 50°C if it is 800 amps and above.

An additional requirement in the type test is the measurement of the contact resistances between the isolating contacts and between the moving and fixed contacts. These points are generally the main sources of excessive heat generation. The voltage drop across the breaker pole is measured for different values of d.c. current which is a measure of the resistance of current carrying parts and hence that of contacts.

Mechanical Tests

A C.B. must open and close at the correct speed and perform such operations without mechanical failure. The breaker mechanism is, therefore, subjected to a mechanical endurance type test involving repeated opening and closing of the breaker. B.S. 116: 1952 requires 500 such operations without failure and with no adjustment of the mechanism. Some manufacture feel that as many as 20,000 operations may be reached before any useful information regarding the possible causes of failure may be obtained. A resulting change in the material or dimensions of a particular component may considerably improve the life and efficiency of the mechanism.

Short Circuit Tests

These tests are carried out in short circuit testing stations to prove the ratings of the C.Bs. Before discussing the tests it is proper to discuss about the short circuit testing stations.

There are two types of testing stations; (*i*) field type, and (*ii*) laboratory type.

In case of field type stations the power required for testing is directly taken from a large power system. The breaker to be tested is connected to the system. Whereas this method of testing is economical for high voltage C.Bs. it suffers from the following drawbacks:

1. The tests cannot be repeatedly carried out for research and development as it disturbs the whole network.
2. The power available depends upon the location of the testing stations, loading conditions, installed capacity, etc.
3. Test conditions like the desired recovery voltage, the RRRV etc. cannot be achieved conveniently.

In case of laboratory testing the power required for testing is provided by specially designed generators. This method has the following advantages:

1. Test conditions such as current, voltage, power factor, restriking voltages can be controlled accurately.
2. Several indirect testing methods can be used.
3. Tests can be repeated and hence research and development over the design is possible.

The limitations of this method are the cost and the limited power availability for testing the breakers.

UNIT 4 HIGH VOLTAGE POWER CABLES

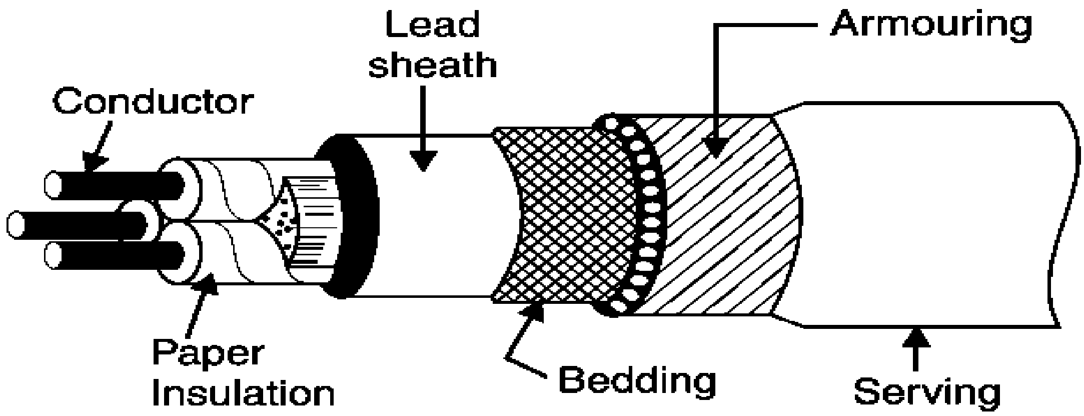
An electrical cable may be defined as a single conductor insulated through its full length; or two or more conductors each provided with its own insulation and laid up together under one outer protective covering.

General construction of cable

The general construction of an underground cable is given below. The underground cable employed for transmission of power at high voltage consists of one central core or a number of cores (two, three or four) of tinned stranded copper or aluminum conductors insulated from each other by paper or varnished cambric or vulcanized bitumen or impregnated paper. A metallic sheath of lead, alloy or of aluminum is provided around the insulation to protect it against ingress of moisture, gases or other damaging liquids (acid or alkalies) in the soil and atmosphere. A metal is essential for sheath because no organic material is sufficiently impervious to moisture. The main advantages of lead sheaths are the comparative ease with which they are made in lead presses, their flexibility and high corrosion resistance while they have got drawbacks of large specific gravity, low mechanical strength, fluidity and small resistance to vibrations. The hardness, mechanical strength and resistance to vibrations of lead sheaths can be considerably improved by adding alloying mixtures (about 1 per cent of copper, tin, bismuth, etc). Aluminum sheaths being cheaper (costing 3.5 times less than the lead sheaths) and having much greater mechanical strength than the lead sheaths, low weight and low fluidity are now being increasingly employed.

For the protection of metallic sheath against corrosion and from mechanical injury a layer of bedding consisting of paper tape compounded with a fibrous material (such as jute, cotton or hessian tape) is provided over the metallic sheath. The compound used should be of such a nature that it does not react with the material of the armouring and the lead sheath but simultaneously it is adhesive enough so as to stick both to the lead sheath and the armouring. Bedding is employed in paper insulated lead covered cables. It is not required in PVC cables.

Over the layer of bedding armouring consisting of one or two layers of galvanized steel wire or steel tape is provided to save the cable from mechanical injury and over the armouring a layer of fibrous material similar to that of bedding, known as serving, is provided in order to protect the armouring.



Electrical insulation techniques

The conductor or electrical circuit is covered with insulating material so that it may prevent leakage of current from the conductor i.e. the insulating material should be extremely high resistive to the flow of electric current through it. The insulating materials used in electric cables must possess the following properties:

- High resistivity
- High flexibility
- High dielectric strength
- Non-inflammability
- Non-hygroscopic
- Highly resistive to moisture, acids or alkalies
- Capability to withstand high rupturing voltages and high temperatures without much deterioration.

No one insulating material possesses all above mentioned qualities, so the type of insulating material used in an electric system depends upon the service for which the system is required. The various types of insulating materials used are:

Rubber: Rubber may be natural or synthetic. Its relative permittivity is between 2 and 3 and its dielectric strength is 30 kV/mm. Though it possesses high insulating qualities but it absorbs moisture readily, softens when heated to a temperature of 60^0C or 70^0C, swells under the action of mineral oils and ages when exposed to light. Hence pure rubber cannot be used as Insulating materials.

Vulcanized India Rubber (VI R): VIR is a good electrical insulator, does not absorb moisture the atmosphere, water proof when new and under favorable conditions remains so for a number of years. The main drawback with VIR is that owing to Sulphur content it attacks copper and, therefore, in cables using VIR insulation the copper conductor is tinned before providing the insulation. Sometimes a layer of pure rubber is also given on the conductor to protect it from sulphation. This has been replaced by PVC insulation.

Impregnated Paper: It is quite cheap, has low capacitance, high dielectric strength (30 kV/mm) and high insulation resistivity (of the order of 10^5 Ω-cm). The main advantage of paper insulation over VIR insulation is that it is superior in heat conductivity and is capable to withstand higher temperature without deterioration. The only disadvantage with paper insulated cable is that it is hygroscopic, and even if it is impregnated with compound, it absorbs moisture, which lowers its insulation resistance. That is why paper insulated cables are always provided with some sort of protective covering and are never left unsealed. Paper insulated cables are rarely used nowadays as PVC and XLPE insulated cables are predominantly used.

Polyvinyl Chloride (PVC): It is synthetic compound. For obtaining this material as cable dielectric or sheath it is processed with certain materials known as plasticizer and its type will depend upon the use of the finished product i.e. PVC. It is inert to oxygen and almost inert to oils and to many alkalies and acids and, therefore, its use is preferred over VIR in extreme environments such as in cement factory or chemical factory. The mechanical properties (i.e. elasticity and recovery from stretching) of PVC are not good as those of rubber. PVC insulated cables are usually employed for low and medium voltage domestic and industrial lights and power installations. This insulation on cables has overtaken all the other insulation on cables because of its low cost.

Silk and Cotton: This is used in low voltage cables. The conductor may have a single layer or double layer covering depending upon the requirements of service. Silk or cotton covered wires are usually used for instruments and motor winding.

Enamel Insulation: Enameled wires are also used for instruments and motor winding. The wires are cheaper than silk and cotton covered wires and therefore for low voltage machines and instruments enameled wires are used.

Classification of insulating materials based on temperature withstand capacity

Class of Insulation	Temperature Range	Insulation Materials
Y	90°C	Cotton, natural silk, paper, paper products, pressboards, etc.

A	105℃	Impregnated cotton, silk, paper, oil enamels, laminated wood, wire enamels based on polyamide resins, etc.
E	120℃	Wire enamels based on polyvinyl formal , polyurethane, phenol, formaldehyde, etc.
B	130℃	Glass fiber, Asbestos, varnished glass fiber, oil modified synthetic resin, etc.
F	150℃	Alkyd, Epoxy, polyester, built up mica with alkyd, etc.
H	180℃	Silicone varnished impregnated glass fiber cloth, mica silicone resin bonded built up mica and combinations of mica and other class materials with suitable bonding materials, etc.
C	Above 180℃	Mica, porcelain, glass quartz, asbestos, built up mica treated glass fiber cloth, etc.

Classification of Cables

The type of cable to be used at a particular location is determined by the mechanical consideration and the voltage at which it is required to operate. Usually the operating voltage determines the type of insulation and the cables are placed in various categories depending upon the voltage for which they are designed. According to the voltage, the cables are classified as:

a) Low voltage (LT) cables for operating voltage up to 1,000 V
b) High voltage (HT) cables for operating voltage up to 11 KV
c) Super tension (ST) cables for operating voltage up to 33 KV
d) Extra high tension (EHT) cables for operating voltage up to 66 KV
e) Extra super voltage cables for operating voltage beyond 132 KV

Low voltage power cables

These cables are meant for use up to 1,000 V. For voltages up to 6.6 KV, the electrostatic stresses developed in cables are very small and thermal conductivity is also of not much importance so no special construction is required. The insulating materials used may be impregnated paper, varnished cambric, vulcanized rubber, or vulcanized bitumen.

a) Single core LT cable: It consists of one circular core of tinned stranded copper or aluminum insulated by layers of impregnated paper or varnished cambric over it and a lead sheath over the insulation. The lead sheath protects the cable against ingress of moisture and mechanical handling.
b) Multicore cable: The multicore cables for use up to 11 KV are of belted type. The belted type cable consists of either circular shaped or oval cores of stranded copper or aluminum conductors wrapped around by impregnated paper and then wormed together. Insulating belt of impregnated paper is provided surrounding the three cores. A lead sheath enclosing the whole is provided for its protection against the entry of moisture. The serving over the armouring consists of a compound and then one layer of impregnated hessian tape. In order to prevent adhesion, a coating of lime wash is applied to the outside of the cable.

High Voltage Power Cables

A high-voltage cable (HV cable) is a cable used for electric power transmission at high voltage. Like other power cables, high-voltage cables have the structural elements of one or more conductors, insulation, and a protective jacket. High-voltage cables differ from lower-voltage cables in that they have additional internal layers in the insulation jacket to control the electric field around the conductor. For circuits operating at or above 2,000 volts between conductors, a conductive shield may surround each insulated conductor. This equalizes electrical stress on the cable insulation.

a) **Super tension Cables:** For cables above 11 KV, a special construction is adopted. For use up to 33 KV, the cables used are screened cables where leakage currents, are conducted to earth through metallic sheaths. Screened cables are of two types i.e H- type and SL type.

i) **H- type Cables:** In the H type cable, no belt insulation is used, but each of the core is insulated with paper to the desired thickness and over this is provided a layer of metallized paper perforated to facilitate the process of impregnation, the coefficient of expansion and contraction is same as that of dielectric.

ii) **SL type cable:** In SL type cables each core is first insulated with an impregnated paper and then each of them, is separately lead sheathed. Now, the three cores are just equivalent to three separate cables, each having its own lead sheath. The three cables are laid up with fillers in the ordinary way, armored and served overall with impregnated hessian tape as usual.

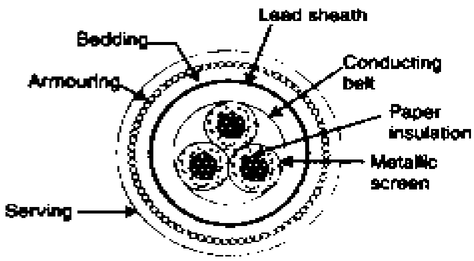


Fig: H type cable

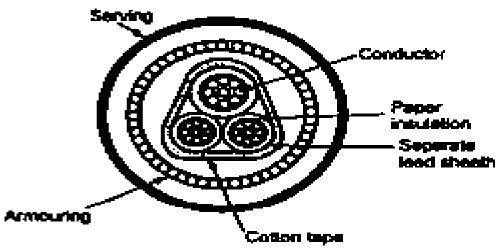


Fig: SL type cable

b) **Extra High Voltage Cables:** The cables considered up to till now are also called solid type and, in such cables, it was assumed that the dielectric is homogeneous and there are no voids in the layer. With this assumption it is necessary to stick to maximum safe dielectric stress of about 4 or 5 KV per mm and also to maximum operating temperature of 50 or 60°C in order to ensure safety for breakdown because the dielectric is far from homogeneous and with the normal manufacturing methods, it is almost impossible to avoid voids in the layers of dielectric. The formation of these voids or vacuous spaces causes unequal voltage stresses and also temperature rise due to leakance current. In order to meet the increased voltage, demand the extra high tension and extra super voltage power cables, useful for 132 KV and above have been developed. In all such cables, the voids have been eliminated by increasing the pressure of the compound and that is why such cables are also called pressure cables.

i) **Oil Filled cables:** Oil filled cable is defined as the cable in which low viscosity oil is kept under pressure either within the cable sheath itself or a containing pipe. The oil in the cable filled the voids in the oil impregnated paper under all conditions of varying loads. In the past, over the years mineral oils are used but recently alkylates (linear deacyl benzene and branched nonyl benzene) become popular because of their low viscosity and their ability to absorb water vapors liberated during ageing of cellulose. Oil filled cables are used for long power transmission or in placed where aerial cable is impracticable to use like sea, underground hydroelectric plant or in power substations having water obstacles.

ii) **Gas pressure cables:** In case of as pressure cables, an inert as like nitrogen at high pressure is introduced. lead sheath and dielectric. The pressure is about 12 to 15 atmospheres. Due to such a high pressure there is a radial compression due to which the ionization is totally eliminated. The working power factors of such cables is also high. The high pressure creates the radial compression to close any voids. The steel pipe is coated with a point to avoid corrosion.

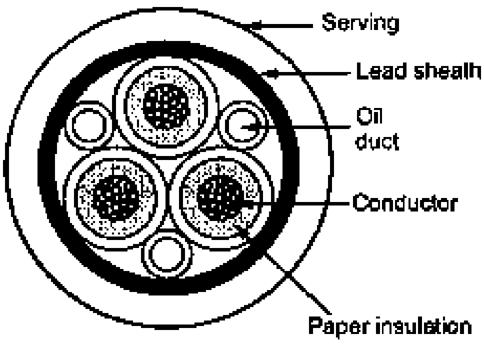


Fig: Oil filled cables

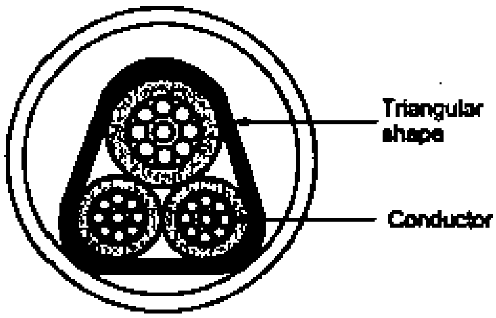


Fig: Gas pressure cables

c) **XLPE Cables:** XLPE is the recognized abbreviation for cross-linked polyethylene. Cross-linking is the effect produced in the vulcanization of rubber and for materials like XLPE the cross-linking process is often described as ‘vulcanization’ or ‘curing’. Small amounts of chemical additives to the polymer enable the molecular chains to be cross-linked into a lattice formation by appropriate treatment after extrusion. The effect of the cross-linking is to inhibit the movement of molecules with respect to each other under the stimulation of heat and this gives the improved stability at elevated temperatures compared with the thermoplastic materials. This permits higher operating temperatures, both for normal loading and under short-circuit conditions, so that an XLPE cable has a higher current rating than its equivalent PVC counterpart.

Fig: XLPE Cable

A high-voltage cable for HVDC transmission has the same construction as the AC cable . The decision between different insulation alternatives for these types of cable is more complex than for AC. For example, material selection will depend on the applicable converter technology, maximum voltage, cable weight, transmission capacity of the system and on the increasing influence of protecting the environment. The oldest technology paper insulated, oil-filled cable has had long and mostly positive service experience in AC as well as DC and is suitable for both converter types. Voltage level is up to 800 kV and cross-sections go to 3000 mm². When applied to HVDC, this insulation system has high power transmission capacity but problems include limitation in system length to about 80 km due to need for pumping stations while, in some cases, the lead sheath and oil in the cable are seen as drawbacks. Mass Impregnated Non-Draining compound (MIND) insulation, XLPE cable Insulation, High Performance Thermoplastic Elastomer (HPTE), etc are the insulations materials used for HVDC cables.

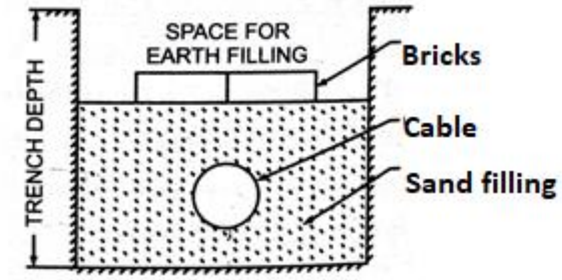
Methods of laying of underground cables

There are three main methods of laying underground cables viz direct laying, draw-in system (or duct/pipe laying) and solid system (or trough laying).

Direct Laying

The cables with efficient steel tape or wire armouring are laid direct as they afford excellent protection from mechanical damage. The paper insulated cables for direct laying are usually served-finish with one or two layers of cotton, jute or hessian treated with bitumen compound. The PVC armoured cables are also laid direct.

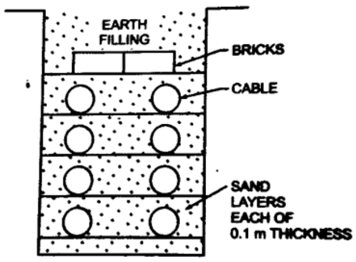
This method of laying underground cable is simple and cheap. In this method of laying underground cables a trench about 1.2 m deep and 0.5 m wide is dug, a layer of (of about 10 cm thickness) fine sand is spread and the cable is laid over this sand bed. The sand does not allow the moisture from ground and thus protects the cable from decay. After the cable has been laid in the trench, it is covered with another layer of sand of about 10 cm thickness and the cable is provided with a wall of bricks on either side and over the top. Then the remaining dug out soil is filled again in the trench. This arrangement is shown in Fig. In cases, when more than one cable is to be laid in the same trench the minimum spacing between any two adjacent cables should be about 30-40 cm (both in horizontal or vertical formation of cable laying) filled with sand or riddled soil between the cables.



Draw-in system

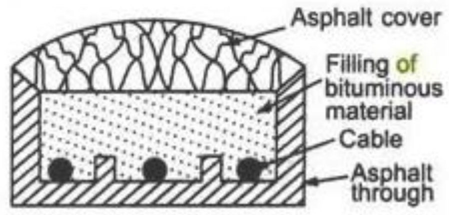
In congested areas where excavation is expensive and inconvenient this system of laying of underground cables is often adopted. In this method of laying of underground cables, a line of conduits, ducts or tubes made of either iron, glazed stoneware, clay or cement concrete are laid in trenches side by side. Separate pipes and ducts are provided are provided for each cable laid in the same duct. The pipes or ducts may also be built up together. The diameter of pipe selected for ducting a cable should always be larger than the outer diameter of the cable to be pulled- in which should be at least 2-3 cm larger than the diameter of the cable than the diameter of the cable for obstruction free pulling. The depth of the trench should be such that the top pipe remains at least 0.6m below the ground level. The width of the trench depends upon the number of pipes to be accommodated. Normally a spacing of 0.25-0.75 m is maintained between two adjacent pipes.

Manhole is the underground chamber where the pipes or ducts terminate and which is employed for pulling-in cable through the ducts and jointing chamber for cables coming in and going out from it. Manhole should be large enough in size to permit a man to enter into without difficulty and its size also depends on the number of ducts terminating from different directions.



Solid system

In solid system of laying underground cables, the cable is laid in troughing, in an open trench/channel dug out in earth along the cable route. After the cable is placed in position, the troughing is filled with bituminous or asphaltic compound and covered over. The cover can be of the same material as the trough. Brick tile covers, placed in position while the compound is still liquid, may also be used. The troughing is of cast iron, stone asphalt or treated wood. This method of laying underground cables is rarely used because of its high cost. Current carrying capacity of the cable is also reduced on account of poor heat dissipation facilities. The other disadvantages are laying and repair require more time, laying and repair cannot be carried out in rainy season.


Asphalt cover
Filling of
bituminous
material
Cable
Asphalt
through

UNIT 5 OVER VOLTAGE PHENOMENON AND INSULATION CO-ORDINATION

The condition of system voltage exceeding the critical limit is Over Voltage, that may be dangerous to the electrical equipment of an installation. Over voltages may occur both as a rise in voltage between phases and between a phase and ground. The voltage stresses on transmission network insulation are found to have a variety of origins. In normal operation, AC (or DC) voltages do not stress the insulation severely.

Classification of Over Voltage

Over Voltage can be;

Common mode: If it happens between phase and earth or phase and frame

Differential mode: If it occurs between phase conductors or between different circuits

It can also be

Temporary: Power frequency over voltage, relatively long duration (up to several seconds)

Transient: Short duration lasting only up to a few mS, oscillatory nature

Over voltage stressing a power system are mainly classified into two main types:

External over voltage

External over voltages are caused by atmospheric discharge such as static charges or lightning strokes and are therefore not related to the system. They are often of such magnitude as to cause considerable stress on the insulation and, in the case of lightning, will vary in intensity depending on how directly the line is struck, i.e directly by the main discharge, directly by a branch or streamer, or by induction due to a flash passing near to but not touching the line. Some of cause of external over voltages are:

a) Direct lightning stroke

b) Electromagnetically induced over voltages due to lightning discharge taking place near the line, called 'side stroke'.

c) Voltages induced due to atmospheric changes along the line length.

d) Electrostatically induced voltages due to charged clouds nearby.

e) Electrostatically induced over voltages due to the frictional effects of small particles like dust or dry snow in the atmosphere or due to change in the altitude of the line.

Internal over voltages

Internal over voltage originate in the system itself and may be transient, dynamic, or stationary. It is generated by changes in the operating conditions of the network. Transient nature will have a frequency unrelated to the normal system frequency and will persist a few cycles only. Dynamic over voltage occurs at normal system frequency and persist only a few seconds. Stationary over voltage also occur at system frequency but may persist for some time, perhaps hours. Internal over voltages can be divided into;

(a) temporary over voltages

(b) switching over voltages

Temporary Over Voltage

Temporary over voltages (also called sustained over voltages) differ from transient natured switching over voltages in that they last for longer durations, typically from a few cycles to a few seconds. They take the form of undamped or slightly damped oscillations at a frequency equal or close to the power frequency. The classification of temporary over voltages as distinct from transient switching over voltages is due mainly to the fact that the responses of power network insulation and surge arresters to their wave shapes are different. Events leading to the generation of temporary over voltages:

Load Rejection

When a transmission line or a large inductive load that is fed from a power station is suddenly switched off, the generator will speed up and the bus bar voltage and frequency will rise. The increase in voltage can be evaluated approximately by,

$$v = \frac{f}{f0} E' \left[\left(1 - \frac{f}{f0}\right)\frac{Xs}{Xc}\right]$$

Where, X_S = the reactance of the generator (approximately the sum of transient reactance of the generator and the transformer)

X_C= the capacitive reactance of the line at the open end at increased frequency

E'= voltage before the load rejection and over-speeding

f_0: the normal frequency

f: instantaneous (increased frequency)

Over voltage may go as high as 2.0 p.u in 400 kV system. Shunt reactors may reduce that to 1.2 to 1.4 p.u. Where E is the voltage behind the transient reactance, which is assumed to be constant over the sub-transient period and equal to its value before the incident, X_S the transient reactance of the generator in series with the transformer reactance, and$X_C$the equivalent capacitive input reactance of the system.

Shunt reactor compensation is quite effective in limiting the over voltage due to load rejection. The synchronous compensator automatically absorbs the reactive power from the system. The time constant of the machine however limits the rate at which the compensator inductive current can be increased. The SVC can change to its maximum current in the inductive range very rapidly and proves to be most effective.

High Capacitance of long EHV lines (Ferranti Effect)

Ac lines have charging current flowing through the series of inductance of line can cause a rise in the output voltage at the receiving end. The Ferranti effect on an uncompensated transmission line is given by:

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

From the given expression,

$$V_S = AV_R + BI_R = \cos h\gamma l \, V_R + Z_C \sin h\gamma l \;\; I_R \ldots \ldots (1)$$

$$I_S = CV_R + DI_R = \frac{1}{Z_C} \sin h\gamma l \, V_R + \cos h\gamma l \;\; I_R \ldots \ldots (2)$$

At no-load condition, I_R =0

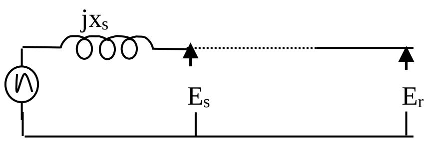
$$V_S = AV_R = \cos h\gamma l \, V_R = \cos h(\alpha + j\beta) l \, V_R$$

For loss-less line, $\alpha = 0$

$$V_S = \cos h(j\beta)lV_R \quad = \cos\beta lV_R$$

$$\frac{VR}{VS} = \frac{1}{Cos\beta_0 l}$$

Where, V_r and V_S are the receiving end and sending end voltages, respectively, and ℓ is the line length (km). β_0 is the phase shift constant of the line per unit length It is equal to the imaginary part of $\sqrt{ZY}$, where Z and Y are the impedance and admittance of the line per unit length. For a lossless line $\beta_0 = \omega\sqrt{LC}$ where L and C are the inductance and capacitance of the line per unit length. β_0 has a value of about 6° per 100 km at normal power frequency.



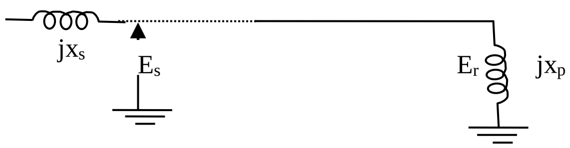
Sending End Voltage	Receiving end Limited voltage	Limiting length $\frac{v_o}{2\pi f}[\cos^{-1} Es / Er]$
400 kV	420 kV	295.76 km
380 kV	420 kV	419.98 km
750 kV	765 kV	189.34 km
735 kV	750 kV	191.23 km
720 kV	750 kV	270.89 km

If no measures will be taken it requires higher insulation level for the equipment's or there exist a limiting length for a set of two end voltages. Hence there must be some compromise between the cost of insulation and the cost associated with countermeasure.

In practice, shunt reactors are always provided in the EHV transmission line for no load conditions. It can overcome the capacitive effect of long line. Let's consider Figure X_P is the inductive reactance of the compensating reactor. It can be derived that the receiving end voltage with shunt reactor is:

$$Er = \frac{Es\cos\theta}{\cos(\beta L - \theta)}$$

Where $\theta = \tan^{-1}\frac{Zc}{X_p}$



$$\cos(\beta L-\theta)=\frac{Es}{Er}\cos\theta$$

or $$\beta L-\theta=\cos^{-1}\left(\frac{Es}{Er}\cos\theta\right)$$

or $$\theta=\beta l-\cos^{-1}\left(\frac{Es}{Er}\cos\theta\right)$$

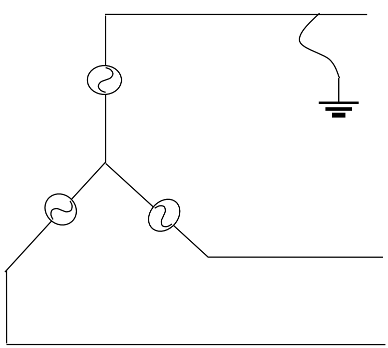
or $$\left(\frac{Zc}{Xp}\right)=\tan\left(\beta l-\cos^{-1}\left(\frac{Es}{Er}\frac{Xp}{\sqrt{Zc^2+Xp^2}}\right)\right)$$

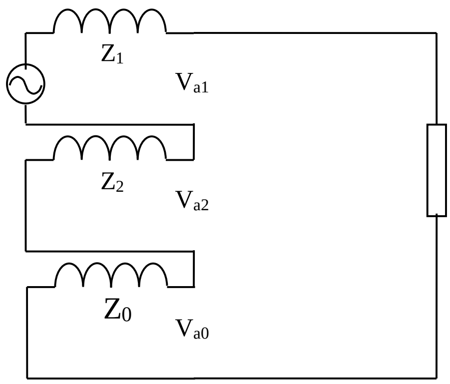
or $$Xp=\frac{Zc}{\tan\left(\beta l-\cos^{-1}\left(\frac{Es}{Er}\frac{Xp}{\sqrt{Zc^2+Xp^2}}\right)\right)}$$

Hence for desired value of Er/Es, X_p can be calculated iteratively

Overvoltage caused by an Unsymmetrical Fault

A single line-to-ground fault will cause the voltages to ground of the healthy phases to rise. In the case of a line-to-ground fault, systems with neutrals isolated or grounded through high impedance may develop over voltages on healthy phases higher than normal line-to-line voltages. Solidly grounded systems will only permit phase-to-ground over voltages well below the line-to-line value. An earth fault factor is defined as the ratio of the higher of the two sound phase voltages to the line-to-neutral voltage at the same point in the system with the fault removed. Suppose a solid line to ground fault occurs on phase A.





It can be shown that for a single line to ground fault, the three sequences (zero, positive & negative sequence) networks are connected in series.

From the sequence networks,

$V_{a1} = E_A - I_{a1}Z_1$

$V_{a2} = -I_{a2}Z_2$

$V_{ao} = -I_{ao}Z_o$

$$I_{a1} = I_{a2} = I_{ao} = \frac{E_A}{Z_1 + Z_2 + Z_0}$$

Also

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$$

$$V_B = V_{a0} + a^2 V_{a1} + aV_{a2}$$

$$= (-I_{ao}Z_o) + a^2 (E_A - I_{a1}Z_1) + a(-I_{a2}Z_2)$$

$$= a^2E_A - a^2I_{a1}Z_1 - aI_{a2}Z_2 - I_{ao}Z_o$$

$$= a^2E_A - \frac{E_A}{(Z_1 + Z_2 + Z_o)}(a^2Z_1 + aZ_2 + Z_o)$$

$$= \frac{a^2E_A(Z_1 + Z_2 + Z_o) - E_A(a^2Z_1 + aZ_2 + Z_o)}{(Z_1 + Z_2 + Z_o)}$$

$$= \frac{(a^2 - 1)Z_0 + (a^2 - a)Z_2}{Z_0 + Z_1 + Z_2} E_A$$

Assuming loss less line, the voltages of healthy phases can be expressed as:

$$V_B = \frac{(a^2 - 1)\, jX_0 + (a^2 - a)\, jX_2}{jX_0 + jX_1 + jX_2} E_A$$

Similarly it can be shown that

$$V_C = \frac{(a - 1)\, jX_0 + (a - a^2)\, jX_2}{jX_0 + jX_1 + jX_2} E_A$$

Considering long length line $X_1 \cong X_2$;

$\Rightarrow$
$$V_B = \left[-\frac{1.5\, X_0/X_1}{2 + X_0/X_1} - j\frac{\sqrt{3}}{2} \right] E_A$$

And
$$V_C = \left[-\frac{1.5\, X_0/X_1}{2 + X_0/X_1} + j\frac{\sqrt{3}}{2} \right] E_A$$

Simplifying we get,

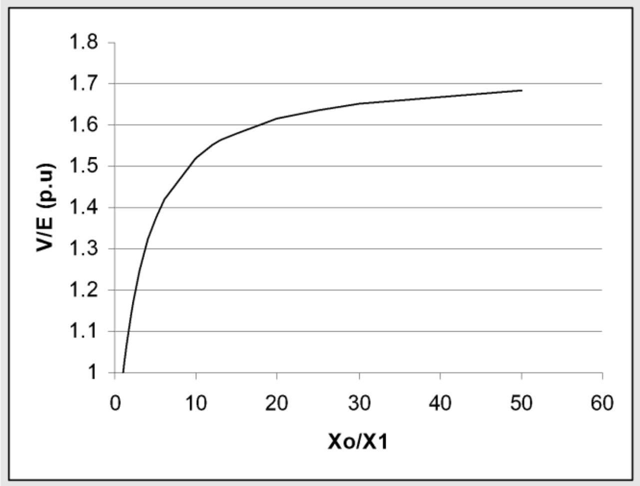
$$|V_B| = |V_C| = \sqrt{3}\,\frac{\sqrt{\left(\frac{X_0}{X_1}\right)^2 + \left(\frac{X_0}{X_1}\right) + 1}}{\left(\frac{X_0}{X_1}\right) + 2}\,E_A$$

For solidly grounded system $X_0 = X_1$

$|VB| = |VC| = EA$

For isolated neutral X_0 = infinity

$|VB| = |VC| = \sqrt{3}\ EA$



For effective grounded system,

$$|V_B| = |Vc| = 0.8 \times \sqrt{3} \times V_A$$

or, $$0.8 \times \sqrt{3} \times E_A = \frac{\left(\sqrt{3} \times \sqrt{\left(\frac{X_0}{X_1}\right)^2 + \left(\frac{X_o}{X_1}\right) + 1}\right)}{\frac{X_o}{X_1} + 2}$$

or, $$\left(0.8\frac{X_o}{X_1} + 1.6\right)^2 = \left(\frac{X_o}{X_1}\right)^2 + \left(\frac{X_o}{X_1}\right) + 1$$

So, $$\frac{X_o}{X_1} = 5.17$$

That is the effective grounding condition means; $\boxed{X_o = 5.17X_1}$

Ferro-resonance

Ferro-resonance or non-linear resonance is a type of resonance in electric circuits which occurs when a circuit containing non-linear inductance is fed from a source that has capacitance, and the circuit is subjected to a disturbance like opening of a switch. It can cause over voltage and pose risk to lines, equipment and personnel. Ferro-resonance occurs when line capacitance resonates with the magnetizing reactance of a transformer core while it goes in and out of saturation.

In a three-phase circuits Ferro- resonance occurs in case of

a. Asynchronous operation of single-phase high voltage switching devices,
b. Fuse blowing or a broken conductor
c. Between the magnetizing impedance of the transformer and the system capacitance of the isolated phase or phases specially (when transformer is energized via an underground cable this effect is even at distribution level)

Ferro-resonance can be described as a voltage multiplication circuit on a power system. Practically, it has been found that using Δ-connection in the secondary can reduce this effect.

Switching Over Voltage (Switching Surges)

Surge is a transient wave of current, voltage or power in an electric circuit. But mostly, 'surge' is used to denote an over voltage with a duration of less than half cycle of the normal voltage waveform. A surge can be positive or negative; can be additive or subtractive form of normal waveform; and is often oscillatory and decaying over time.

With the increase in transmission voltages needed to fulfil the required increase in transmitted powers, switching surges have become the governing factor in the design of insulation for EHV and UHV systems. Lightning over voltages come as a secondary factor in these networks.

Below 300 kV: lightning o/v dominant, switching o/v not much considered

In the range of 300 to 700 kV: both switching and lightning o/v need to be considered for design purposes

In the UHV range (>700 kV): switching surges are the chief concern

Switching transients (over voltage) in a transmission line occurs due to

- Presence of line inductance and capacitance
- Electrostatic and electromagnetic energy associated with the capacitor and inductor.
- This occurs whenever there is sudden change in operating condition.

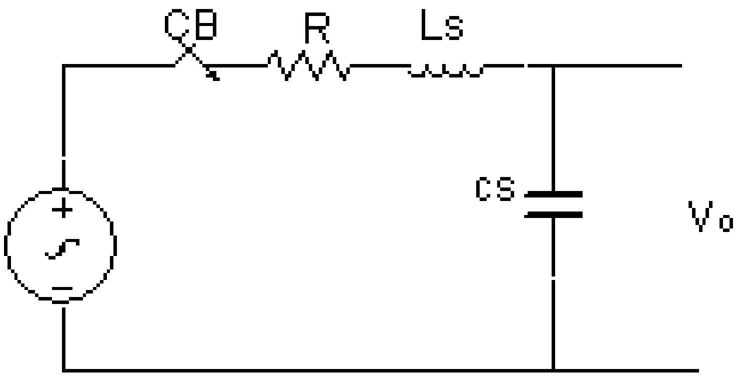
The magnitude and frequency of this type of over voltage depend mainly on-line parameters (Resistance, capacitance and Inductance). Over-voltage magnitude could be up to nearly 4 p. u. and could last up to few milliseconds.

In a power system the major causes of a switching over voltages are:

- Energizing an unloaded transmission line
- De-energizing the transmission line
- Interruption of capacitive current by circuit breaker
- Current chopping by Circuit breaker
- Ferro Resonance

Energization of an Unloaded Transmission Line

When an unloaded transmission line is switched on, the sinusoidal supply voltage is suddenly applied to it as represented by the single-phase circuit as shown in the Figure. The transformer is represented by its leakage inductance and the line by its inductance and capacitance to ground. The switching operation is affected at an instant T seconds beyond that of zero voltage. The voltage across the capacitor C is the one under study here, as it represents the voltage at the open-circuit end of the line.



Let's consider a lumped parameter model circuit of a transmission line at no load. Since, the frequency of switching over voltage is in the order of kHz. Hence, even with the applied sinusoidal voltage of 50 Hz, the switching over voltage could be simulated by an instantaneous sinusoidal voltage as step voltage at the instant of switching.

In the circuit E be the Instantaneous Voltage during switching and V_0 be Voltage equivalent to trapped charge in Capacitor. If $V_C(t)$ is the voltage at the receiving end of the transmission line immediately after CB contacts gets closed. It can be obtained by Formulating the dynamic mathematical model of the system. The formulation can be solved by classical method or by using the Laplace Transform Technique.

$$\frac{E-V_o}{s}=(R+Ls+\frac{1}{Cs})I_C(s)$$

$$I_C(s)=\frac{\left(E-V_o\right)}{s(R+Ls+\frac{1}{Cs})}$$

Also,

$$V_C(s) = I_C(s)\frac{1}{Cs} + \frac{V_o}{s}$$

$$= \frac{(E-V_o)\big/ s}{(R + Ls + \frac{1}{Cs})} \times \frac{1}{Cs} + \frac{V_o}{s}$$

$$= \frac{(E-V_o)}{s}\left[\frac{1}{RCs + LCs^2 + 1}\right] + \frac{V_o}{s}$$

$$= \frac{E-V_o}{s}\left[\frac{1\big/ LC}{s^2 + \frac{R}{L}s + \frac{1}{LC}}\right] + \frac{V_o}{s}$$

$$= \frac{E-V_o}{s}\left[\frac{1\big/ LC}{(s+\alpha)^2 + \omega^2}\right] + \frac{V_o}{s}$$

Where,

$$\alpha^2 + \omega^2 = 1\big/ LC \quad \& \, 2\alpha = R\big/ L$$

$$\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \quad \& \, \alpha = \frac{R}{2L}$$

Thus;

$$V_C(s) = \frac{E-V_o}{LC}\left[\frac{1}{s\left((s+\alpha)^2 + \omega^2\right)}\right] + \frac{V_o}{s}$$

Applying partial fraction expression:

$$V_C(s) = \frac{E - V_o}{(\alpha^2 + \omega^2)LC}\left[\frac{1}{s} - \frac{s + 2\alpha}{(s+\alpha)^2 + \omega^2}\right] + \frac{V_o}{s}$$

$$= E - V_o\left[\frac{1}{s} - \frac{s + 2\alpha}{(s+\alpha)^2 + \omega^2}\right] + \frac{V_o}{s}$$

Taking the Laplace inverse,

$$V_C(t) = (E - V_o)\left[1 - e^{-\alpha t}(\cos\omega t + \frac{\alpha}{\omega}\sin\omega t)\right] + \mathrm{V_O}$$

The above expression can be rewritten as:

$$V_C(t) = (E - \mathrm{V_O})\left[1 - e^{-\alpha t}\frac{\sqrt{\alpha^2 + \omega^2}}{\omega}\left\{\frac{\omega}{\sqrt{\alpha^2 + \omega^2}}\cos\omega t + \frac{\alpha}{\sqrt{\alpha^2 + \omega^2}}\sin\omega t\right\}\right] + V_o$$

$$= (E - V_o)\left[1 - e^{-\alpha t}\frac{\sqrt{\alpha^2 + \omega^2}}{\omega}\cos(\omega t - \phi)\right] + V_o$$

$$\textit{In above, } \cos\phi = \frac{\omega}{\sqrt{\alpha^2 + \omega^2}}, \sin\phi = \frac{\alpha}{\sqrt{\alpha^2 + \omega^2}} \Rightarrow \tan\phi = \frac{\alpha}{\omega} \;\; or, \phi = \tan^{-1}\frac{\alpha}{\omega}$$

Special Cases:

i) Neglecting R (lossless line); $\alpha = 0$

$V_C(t) = (E - V_0)(1 - \cos\omega t) + V_0$

No trap charge, $V_c$max=2 p.u

Trap charge of -1 p.u, $V_c$max $= 3$ p.u

Trap charge of1 p.u, $V_c$max $= 1$ p.u

ii) Considering line resistance

No trap charge, $V_c$max= close to 2 p.u and decaying

Trap charge of -1 p.u, $V_c$max $=$ close to 3 p.u and decaying

Trap charge of1 p.u, $V_c$max $= 1$ p.u

De-energizing the transmission line

De-energizing may be due to either disconnection of load from transmission line or from discriminating the fault. With disconnection of the switch the model circuit would be similar to that of energizing. Here consideration of Trap charge becomes more important. Hence same expression for over voltage is applicable here too.

As we have seen that the switching over voltage with a lossy system reduces with time. Hence, reducing the switching over voltage in a practical system means, reducing its first peak i.e. maximum value. So, let's re consider a switching over voltage expression derived in section-1.

$$V_c(t) = (E - V_o)\left[1 - e^{-\alpha t}\frac{\sqrt{\alpha^2+\omega^2}}{\omega}\cos(\omega t - \phi)\right] + V_o$$

For $V_c(t)$ to be maximum,

$$\frac{dV_c(t)}{dt} = 0$$

Therefore,

$$E\left[\frac{\sqrt{\alpha^2+\omega^2}}{\omega} + \alpha e^{-\alpha t}\frac{\sqrt{\alpha^2+\omega^2}}{\omega}\cos(\omega t - \phi) + \varpi e^{-\alpha t}\frac{\sqrt{\alpha^2+\omega^2}}{\omega}\sin(\omega t - \phi)\right] = 0$$

$$\omega\sin(\omega t - \phi) + \alpha\cos(\omega t - \phi) = 0$$

$$\tan(\omega t - \phi) = -\frac{\alpha}{\omega} = -\tan\phi = \tan(\pi - \phi)$$

$$\omega t - \phi = \pi - \phi$$

$$t = \pi/\omega$$

Hence $V_c(max)$ without trap charge can be expressed as:

$$V_c(t)MAX = E\left[1 - e^{-\pi\alpha/\omega}\frac{\sqrt{\alpha^2+\omega^2}}{\omega}\cos(\pi - \phi)\right]$$

Also from fundamental principle we know that to increase the transient to decay its essential to increase the circuit resistance. Also in the above expression for $V_c(t)MAX$; With increasing R:

$\alpha = \dfrac{R}{2L}$ increases and ω decreases

Results in $\dfrac{\alpha}{\omega}$ to increase and hence $e^{-\pi\alpha/\omega}$ decreases

And also $\phi = \tan^{-1}\dfrac{\alpha}{\omega}$ increase i.e. $\cos(\pi-\varphi)$ becomes less negative value

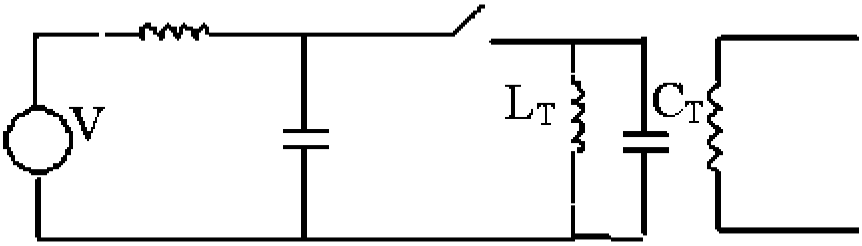
$e^{-\pi\alpha/\omega} \times \cos(\pi-\varphi)$ further less and thus $V_c(t)MAX$ comes closer to E

Thus, the maximum switching over voltage can be reduced by inserting more resistance in the system. Addition of more resistance means more loss. But the switching over voltage can be reduced just by inserting a resistance during the switching This is known as resistance switching.

Interruption of inductive current/current chopping

Usually, CB is designed to interrupt very high magnitude of fault current. In case of low current CB assumes current zero even it is not and the contacts of CB separates. When this CB is used to disconnect the transformer at no load,

a. The current is very small
b. current is highly inductive



If CB's contacts get separated but and I is not zero. There is some electromagnetic energy stored in transformer core which is equal to $\frac{1}{2} I_L^2 L$

Where, I_L = Instantaneous current when CB's contacts get separated.

If this energy gets some path, it tries to get released.

Energy in inductor $= \frac{1}{2} I_L^2 L_L$ &

Electrostatic energy in capacitor $= \frac{1}{2} C_T V^2$

Total Energy $= \frac{1}{2} I_L^2 L + \frac{1}{2} C_T V^2$

After the CB interruption,

both the energy gets converted into electrostatic energy.

So, Energy $= \frac{1}{2} C_T V_{new}^2$

Therefore,

$$\frac{1}{2} C_T V_{new}^2 = \frac{1}{2} I_L^2 L + \frac{1}{2} C_T V^2$$

$$V_{new} = \sqrt{\frac{L_T}{C_T} I_L^2 + V^2}$$

Case-1: If I_L is interrupted at $I_L(t)=0$

There will be no over-voltage. $V_{new} = V$

Case-2: If I_L is interrupted at peak value i.e. $I_L(t)$ at peak

Here, V=0

$$V_{new} = \sqrt{I_L^{\,2} \frac{L_T}{C_T}} = I_{LMax}\sqrt{\frac{L_T}{C_T}}$$

$$\sqrt{\frac{L_T}{C_T}} = Surge\,impedance\;of\;transformer$$

Surge impedance of transformer is greater than that of transmission line as:

L_T is high and C_T is low.

Lightning Over Voltages

Lightning discharges are the main external cause of over voltage in power system. Lightning phenomenon is a peak discharge of charge accumulated in the clouds. Lightning protection system provides a safe pathway for the charge accumulated in the clouds to the earth.

Lightning is produced in an attempt by nature to maintain a dynamic balance between the positively charged ionosphere and the negatively charged earth. Over fair-weather areas there is a downward transfer of positive charges through the global air-earth current. This is then counteracted by thunderstorms, during which positive charges are transferred upward in the form of lightning.

Lightning Phenomenon in Brief

During thunderstorms, positive and negative charges are separated by the movements of air currents forming ice crystals in the upper layer of a cloud and rain in the lower part. The cloud becomes negatively charged at the bottom and has a larger layer of positive charge at its top. As the separation of charge proceeds in the cloud, the potential difference between the centers of charges increases and the vertical electric field along the cloud also increases. The total potential difference between the two main charge centers may vary from l00 MV to 1000 MV. Only a part of the total charge-several hundred coulombs-is released to earth by lightning; the rest is consumed in intercloud discharges. The electrode separation i.e. cloud to cloud or cloud to ground is very large – 10 km or more.

The channel to earth is first established by a stepped discharge called a **leader stroke**. The **leader** is initiated by a breakdown between polarized water droplets at the cloud base caused by the high electric field, or a discharge between the negative charge mass in the lower cloud and the positive charge pocket below it. The velocity of the stepped leader is relatively slow about 0.10% of the speed of light. This is not visible to naked eye. As the **downward leader** approaches the earth, an **upward leader**, also called **streamer** begins to proceed from earth before the former reaches earth. The **downward leader** joins the **streamer** one at a point referred to as the **striking point**. This is the start of the **return stroke**, which progresses upward like a travelling wave on a transmission line. The return stroke's velocity is in between 10 to 30% that of light. It is highly visible to the eye. It carries heavy current of about 33KA. The temperature of this channel exceeds 50,000 F. The rapid increase in temperature creates shock waves that we hear as thunder.

A second leader starts downwards 10 to 100ms after first stroke and is called **dart leader**. It has no pronounced steps and proceeds directly toward ground. The current is usually 40% of the first stroke.

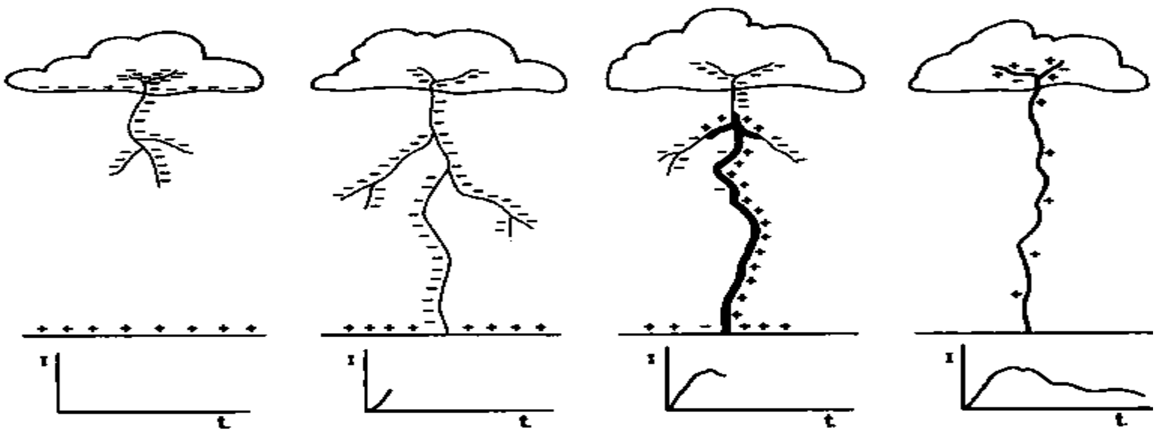
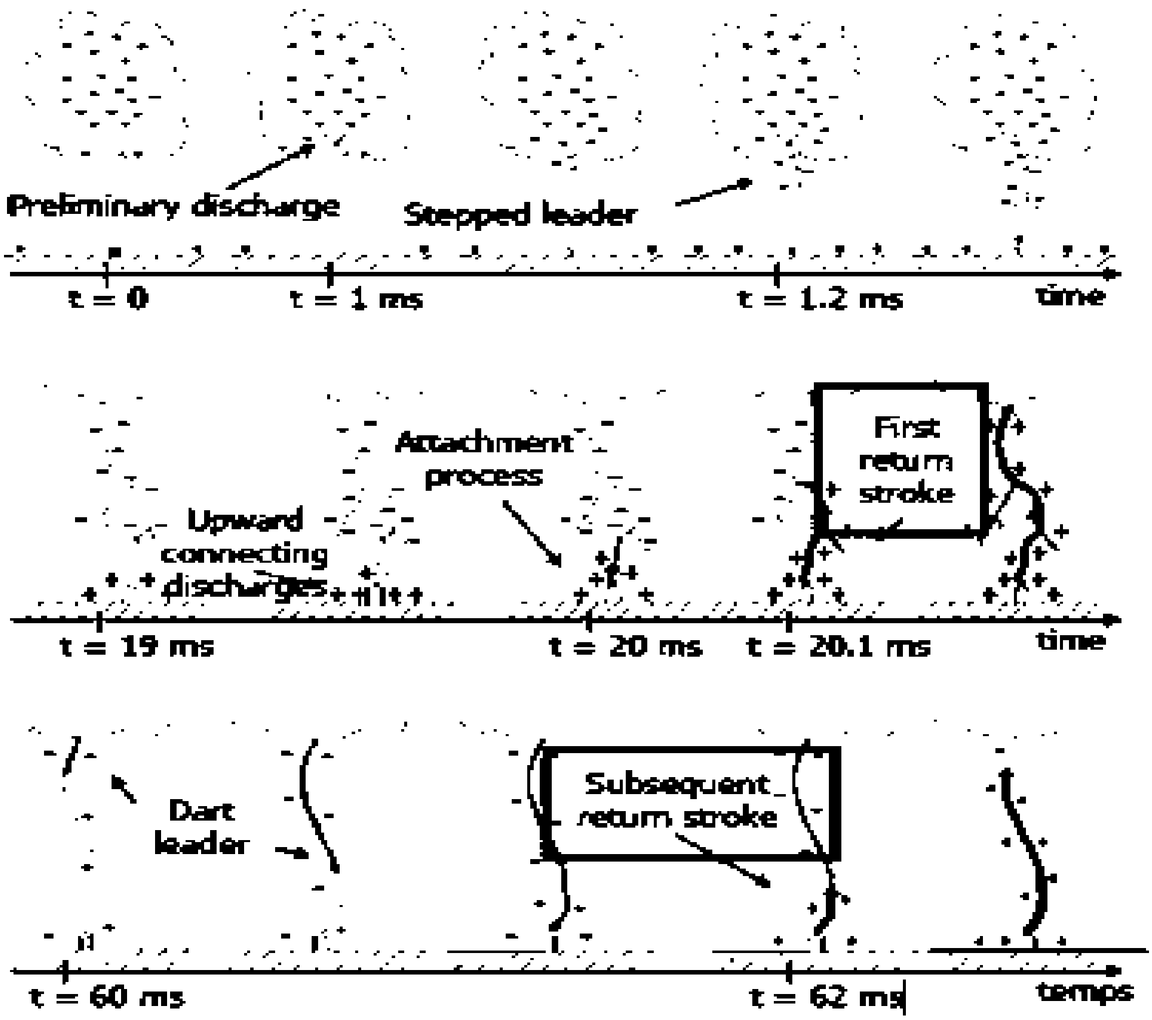
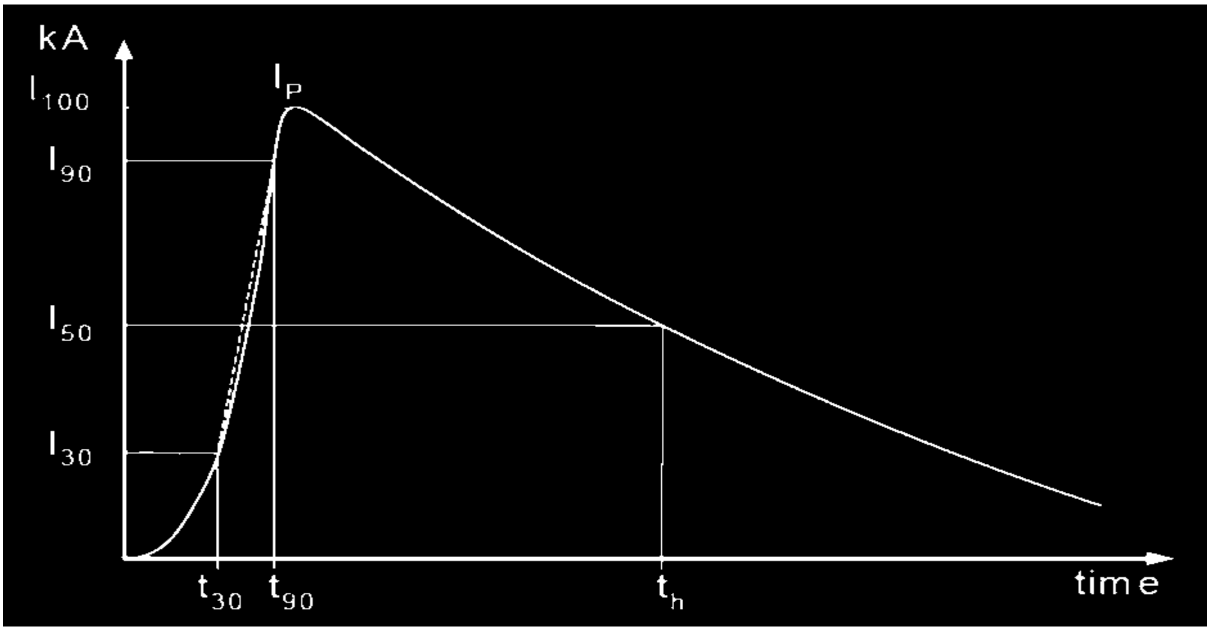


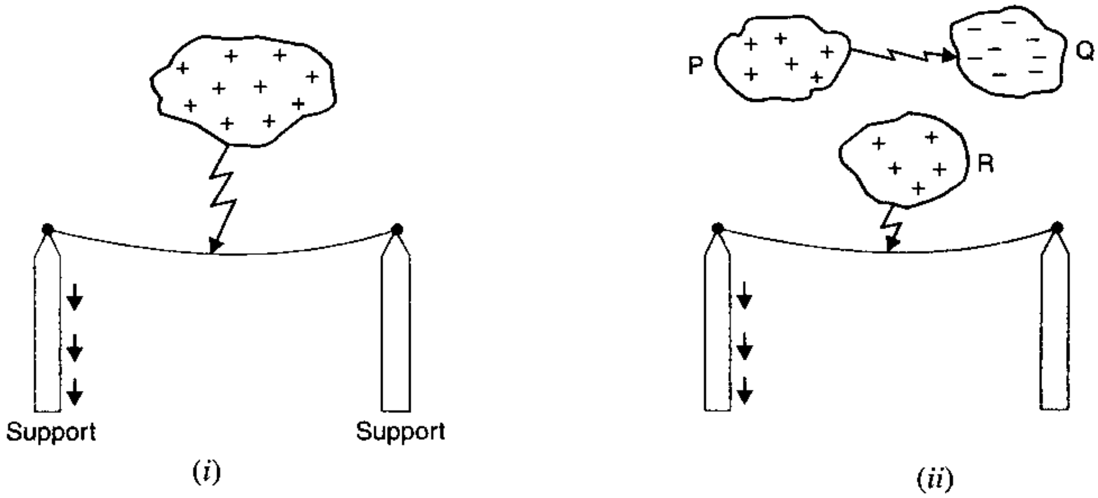
Fig. 14.1 Developmental stages of a lightning flash and the corresponding current surge.





Direct Stroke

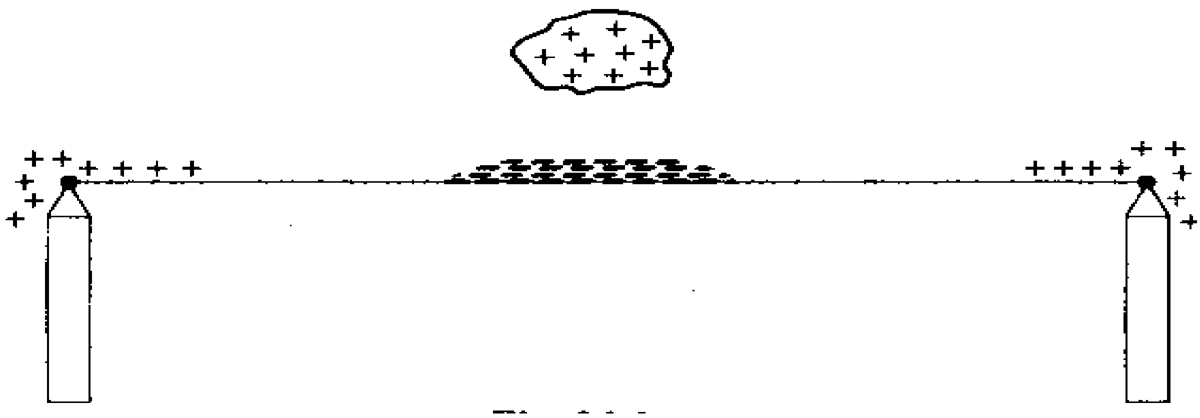
When the lightning discharge (current path) is directly from the cloud to the object (e.g. a transmission line).



Initially, clouds P, Q and R are stable. If somehow P and Q come closer and discharge takes place between them, cloud R suddenly becomes unstable and veers down to earth.

Indirect Stroke

Indirect strokes result from the electro statically induced charges on the conductors due to the presence of charged clouds.



A positively charged cloud is above the line and induces a negative charge on the line by electrostatic induction. This negative charge, however, will be only on that portion of the line right under the cloud and the portions of the line away from it will be positively charged as shown in Figure.

The induced positive charge leaks slowly to earth via the insulators. When the cloud discharges to earth or to another cloud, the negative charge on the wire is isolated as it cannot flow quickly to earth over the insulators. The result is that negative charge rushes along the line is both directions in the form of travelling waves. It may be worthwhile to mention here that majority of the surges in a transmission line are caused by indirect lightning strokes.

Insulation Co-ordination

The term Insulation Co-ordination was originally introduced to arrange the insulation levels of the several components in the transmission system in such a manner that an insulation failure, if it did occur, would be confined to the place on the system where it would result in the least damage, be the least expensive to repair, and cause the least disturbance to the continuity of the supply.

The present usage of the term is broader. Insulation co-ordination now comprises the selection of the electric strength of equipment in relation to the voltages which can appear on the system for which the equipment is intended. The overall aim is to reduce to an economically and operationally acceptable level the cost and disturbance caused by insulation failure and resulting system outages.

To keep interruptions to a minimum, the insulation of the various parts of the system must be so graded that flashovers only occur at intended points. With increasing system voltage, the need to reduce the amount of insulation in the system, by proper co-ordination of the insulating levels become more critical.

Terminology

Nominal System Voltage: It is the r.m.s. phase-to-phase voltage by which a system is designated.

Maximum System Voltage: It is the maximum rise of the r.m.s. phase-to-phase system voltage.

Rated Short Duration Power Frequency Withstand Voltage: This is the prescribed r.m.s. value of sinusoidal power frequency voltage that the equipment shall withstand during tests made under specified conditions and for a specific time, usually not exceeding one minute.

Protective Level of Protective Device: These are the highest peak voltage value which should not be exceeded at the terminals of a protective device when switching impulses and lightning impulses of standard shape and rate values are applied under specific conditions.

Basic Lightning Impulse Insulation Level (BIL): The crest value of a standard lightning impulse for which the insulation exhibits a 90% probability of withstand (10% probability of failure) under specified conditions.

Basic Switching Impulse Insulation Level (BSL): The crest value of a standard switching impulse for which the insulation exhibits a 90% probability of withstand (10% probability of failure) under specified conditions.

Factor of Earthing: This is the ratio of the highest r.m.s. phase-to-earth power frequency voltage on a sound phase during an earth fault to the r.m.s. phase-to-phase power frequency voltage which would be obtained at the selected location without the fault. This ratio characterizes, in general terms, the earthing conditions of a system as viewed from the selected fault location.

Effectively Earthed System: A system is said to be effectively earthed if the factor of earthing does not exceed 80%, and non-effectively earthed if it does. [Note: Factor of earthing is 100% for an isolated neutral system, while it is 57.7% for a solidly earthed system. In practice, the effectively earthed condition is obtained when the ratio $x_0/x_1 < 3$ and the ratio $r_0/x_1 < 1$.

Insulation coordination means the correlation of the insulation of the various equipment in a power system to the insulation of the protective devices used for the protection of those equipment against over-voltages. In a power system various equipment like transformers, circuit breakers, bus supports etc. have different breakdown voltages and hence the volt-time characteristics. In order that all the equipment should be properly protected it is desired that the insulation of the various protective devices must be properly coordinated. The basic concept of insulation coordination is illustrated in the Figure below. Curve A is the volt-time curve of the protective device and B the volt-time curve of the equipment to be protected. This figure shows the desired positions of the volt-time curves of the protecting device and the equipment to be protected. Thus, any insulation having a withstand voltage strength in excess of the insulation strength of curve B is protected by the protective device of curve A. It is, therefore, necessary to understand the meaning of this expression.

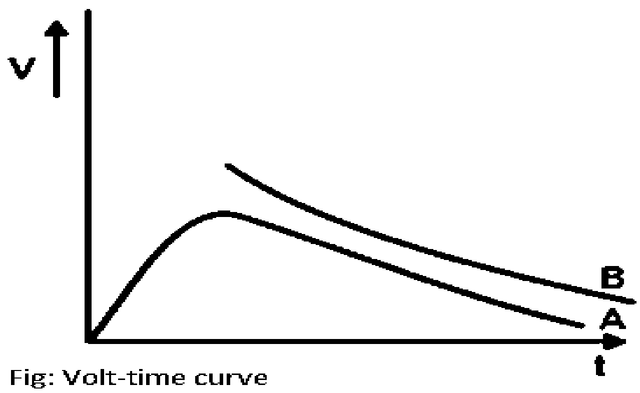
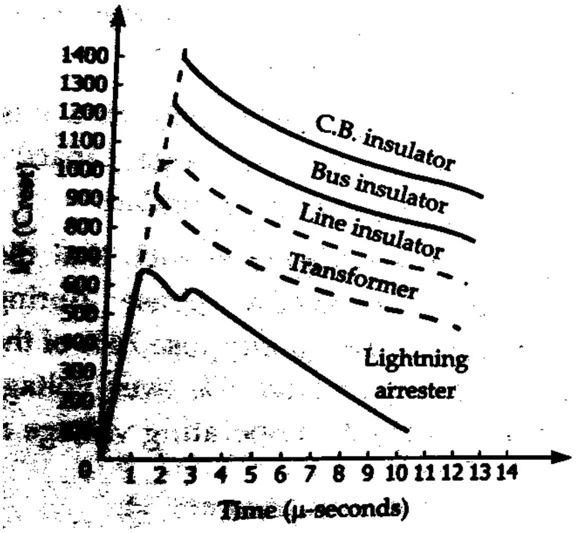


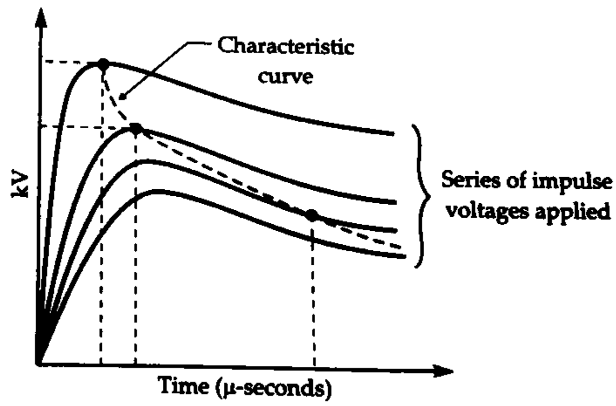
Fig: Volt-time curve
A (protecting device) and B (Device to be protected)

Volt-Time Curve

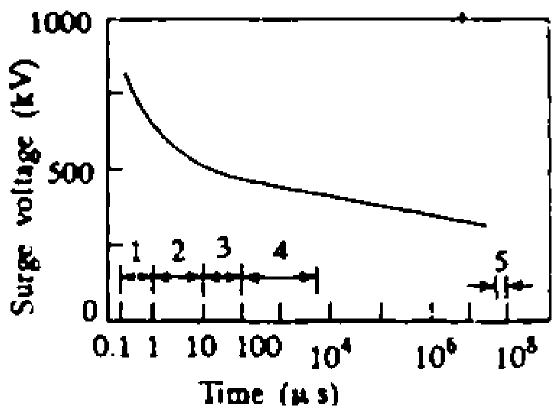
The breakdown voltage for a particular insulation of flashover voltage for a gap is a function of both the magnitude of voltage and the time of application of the voltage. The volt-time curve is a graph showing the relation between the crest flashover voltages and the time to flashover for a series of impulse applications of a given wave shape.

For the construction of volt-time curve, waves of the same shape but of different peak values are applied to the insulation whose volt-time curve is required.



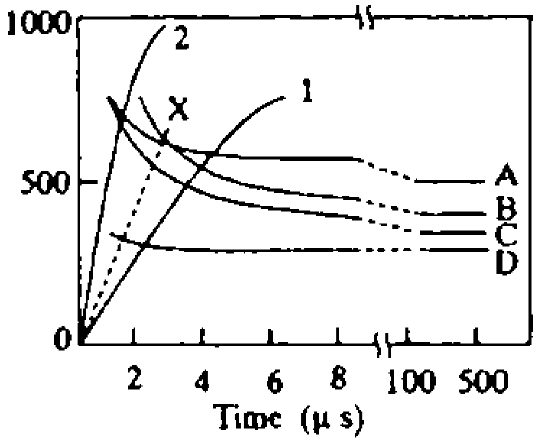


A lightning arrester protects the transformer insulation in the entire time region. The rod gap protects the transformer insulation, only if the rate of rise of surge is less than the critical slope (curve X). Thus, if the surge voltage rise is as shown by curve 1, rod gap flashes and protects the transformer. If the surge voltage rise follows curve 2, only the surge diverter can protect the transformer insulation.



Typical transformer characteristic

1. For steep fronted lightning surge
2. Slow fronted lightning surge
3. Fast switching surge
4. Slow switching surge
5. Power frequency (1 minute withstand voltage)

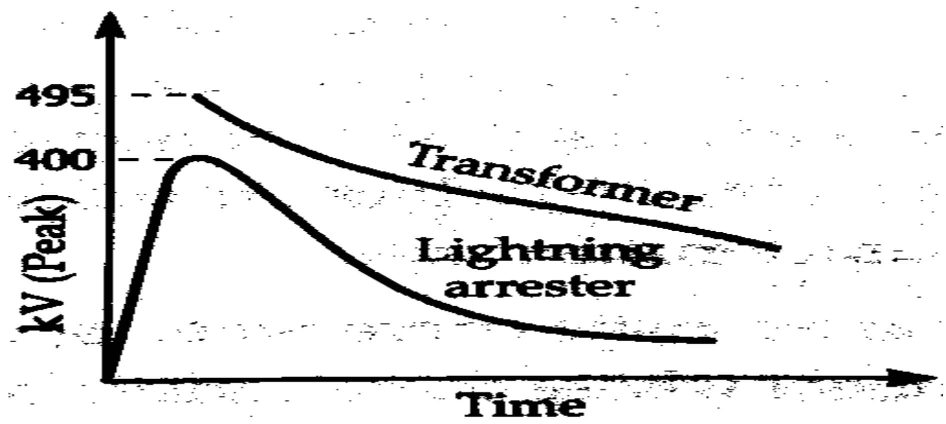


Transformer — A
Rod gaps — B and C
Surge diverter — D
Critical slope — X

Significance of v-t curve

- v-t curve gives an idea of FOV at different values of time of application of various voltages. So, it gives an idea of protection level of various equipment.
- Useful in making proper insulation coordination.
- Also helpful in determining the relative margin in protection level of various sub-station equipment.

For example, let us suppose that a L.A. operates at 400 kV. If the margin for the protection required is 15% plus 35 kV between LA and transformer, then the insulation level of transformer should be 495 kV.



The ideal requirements of a protective device connected in parallel or in shunt are:

(a) It should not usually flashover for power frequency over-voltages.
(b) The volt-time characteristics of the device must lie below the withstand voltage of the protected apparatus or insulation. The marginal difference between the above two should be adequate to allow for the effects of distance, polarity, atmospheric conditions, changes in the characteristics of the devices due to aging, etc.
(c) It should be capable of discharging high energies contained in surges and recover insulation strength quickly.
(d) It should not allow power frequency follow-on current to flow.

Equipment Insulation Level and Insulation Coordination of Sub-stations

For steep fronted lightning waves at sub-stations and at different points on lines, the voltages at sub-stations may exceed the protective level depending on the distances involved and the diverter locations. Hence, it is necessary to decide the number of locations for diverters to optimize the overall cost. For high voltage sub-stations, it is usual to install surge diverters between a transformer and its circuit breaker, in order to protect the transformer from current chopping and the overvoltage due to it. Further, nearness of the diverter to the transformer offers better protection.

- The basic insulation level is often determined by giving a margin of 30% to the protective level of surge diverter and selecting the next nearest standard BIL.

- When a surge diverter is used to give switching surge protection also, the margin allowed is only 15%.

- The insulation level for lines and other equipment is to be chosen separately. The selection of this level for lines depends on the atmospheric conditions, the lightning activity, insulation pollution present and the acceptable outrage or failure rate of the line.

- The protective level of the sub-station insulation depends on the station location, the protective level of the diverter, and the line shielding used. The line insulation in the end spans near the sub-station is normally reduced to limit the lightning over voltages reaching the sub-station.

- In a sub-station, the busbar insulation level is the highest to ensure continuity of supply. The circuit breakers, isolators, instrument and relay transformers, etc. are given the next lower level. Since the power transformer is the costly and sensitive device, the insulation level for it is the lowest.

The standard values of BIL for system voltages from 145 to 765 are given in tables below:

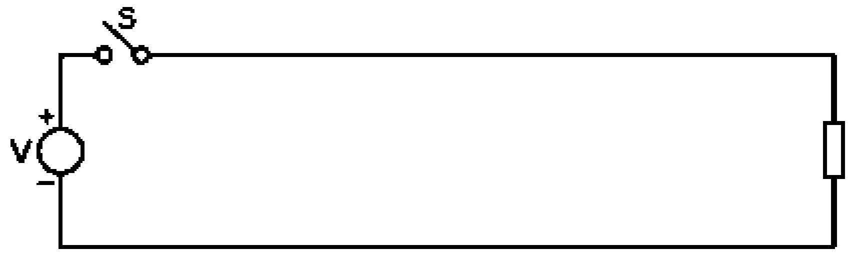
Highest voltage of the system equipment	Impulse withstand voltage for standard impulse waves		Power frequency withstand voltage with respect to earth	
	Full insulation	Reduced insulation	Full insulation	Reduced insulation
kV (rms)	kV (peak)	kV (peak)	kV (rms)	kV (rms)
145	650	550	275	230
		450		185
245	1050	—	460	—
		900	—	395
		825	—	360
		750	—	325
362	—	1300	—	570
		1175	—	510
		1050	—	461
420		1675	—	740
		1550	—	680
		1425	—	630
		1300	—	570
525		1800	—	790
		1675	—	740
		1550	—	680
		1425	—	630
765		2400	—	1100
		2100	—	980
		1950	—	920
		1800	—	870

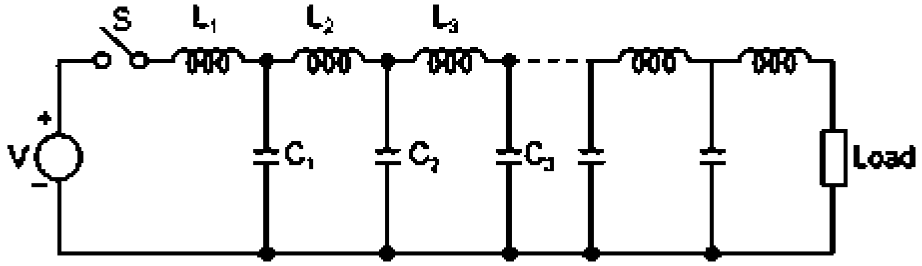
Travelling Waves

Travelling waves are the current and voltage waves which travel from the sending end of a transmission line to the other end.

Generally, the transient behavior of various circuits is studied with lumped parameters. However, there are some parts of a power system where this approach is inadequate. The most obvious example is the transmission line. Here the parameters L, C and R are uniformly distributed over the length of the line. For steady state operation of the line the transmission lines could be represented by lumped parameters but for the transient behavior of the lines they must be represented by their actual circuits i.e., distributed parameters. We say that for a 50 Hz supply and short transmission line the sending end current equals the receiving end current and the change in voltage from sending end to receiving end is smooth.

To understand the travelling wave phenomenon over transmission line, consider the circuit shown below. The line is assumed to be lossless. Let L and C be the inductance and capacitance respectively per unit length of the line. The line has been represented by a large number of L and C sections.





Equivalent Section of a Long Transmission Line

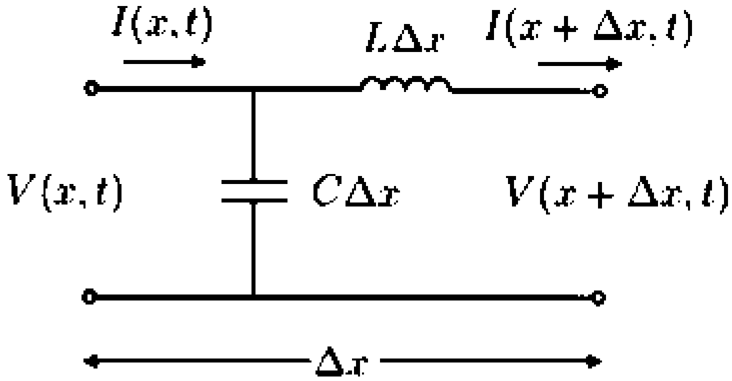
When the switch is closed at the transmission line's starting end, voltage will not appear instantaneously at the other end. This is caused by the transient behavior of inductor and capacitors that are present in the transmission line.

Water Channel Analogy: The closing of the switch is similar to opening the valve at the end of a channel, thereby admitting water to the channel from some reservoir behind. When the valve is opened the channel does not get filled up instantaneously. We observe the water advancing down the channel. At any instant the channel ahead of the wave front is dry while that behind is filled with water to the capacity.

Similarly, when the switch S is closed the voltage does not appear instantaneously at the other end. When switch S is closed, the inductance L_1 acts as an open circuit and C_1 as short circuit instantaneously. The same instant the next section cannot be charged because the voltage across the capacitor C_1 is zero. So, unless the capacitor C_1 is charged to some value whatsoever, charging of the capacitor C_2 through L_2 is not possible which, of course, will take some finite time. The same argument applies to the third section, fourth section and so on. So, we see that the voltage at the successive sections builds up gradually. This gradual build-up of voltage over the transmission line conductors can be regarded as though a voltage wave is travelling from one end to the other end and the gradual charging of the capacitances is due to the associated current wave.

Expressions for the relation between the voltage and current waves and their velocity of propagation

Suppose that the wave after time t has travelled through a distance x. Since we have assumed lossless lines whatever is the value of voltage and current waves at the start, they remain same throughout the travel. Consider a distance dx which is travelled by the waves in time dt. The electrostatic flux is associated with the voltage wave and the electromagnetic flux with the current wave.



The electrostatic flux which is equal to the charge between the conductors of the line up to a distance x is given by;

$q = VCx$ ……………(1)

The current in the conductor is determined by the rate at which the charge flows into and out of the line.

$I = \frac{dq}{dt} = VC\frac{dx}{dt}$ ………………(2)

Here $\frac{dx}{dt}$ is the velocity of the travelling wave over the line conductor and let this be represented by v. Then;

$I = VCv$ …………(3)

Similarly, the electromagnetic flux linkages created around the conductors due to the current flowing in them up to a distance of x is given by;

$\psi = ILx$ ……………….(4)

where, ψ is electromagnetic flux and L is inductance.

The voltage is the rate at which the flux linkages link around the conductor;

$V = IL\frac{dx}{dt} = ILv$ ……….(5)

Dividing equation (5) by (3), we get

$\frac{V}{I} = \frac{ILv}{VCv} = \frac{IL}{VC}$

Or, $\frac{V^2}{I^2} = \frac{L}{C}$

Or, $\frac{V}{I} = \sqrt{\frac{L}{C}} = Z_n$

The expression is a ratio of voltage to current which has the dimensions of impedance and is therefore, here designated as surge impedance of the line. It's also known as the **natural impedance** as this impedance has nothing to do with the load impedance. It is purely a characteristic of the transmission line. The value is about 400 ohms for O/H lines and 40 ohms for cables.

Next, multiplying equations (3) with (5), we get

$VI = VCv\ ILv = VILCv^2$

Or, $v^2 = \frac{1}{LC}$

Or, $v = \frac{1}{\sqrt{LC}}$

Expressions for L and C for overhead lines are

$$L = 2 \times 10^{-7} \ln\left(\frac{d}{r}\right)\ H/m$$

$$C = \frac{2\pi\varepsilon}{\ln\left(\frac{d}{r}\right)}\ F/m$$

Substituting these values in above equation, the velocity of propagation of the wave

$$v = \frac{1}{\sqrt{2\times 10^{-7} \ln\left(\frac{d}{r}\right) \cdot \frac{2\pi\varepsilon}{\ln\left(\frac{d}{r}\right)}}} = 3 \times 10^8\ m/s$$

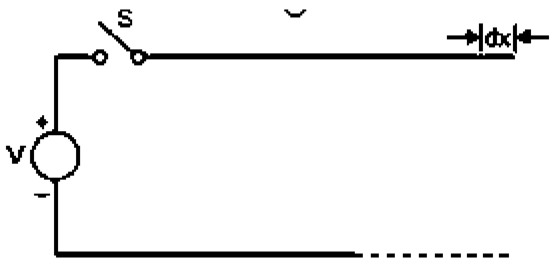
This is the velocity of light. This means the velocity of propagation of the travelling waves over the O/H lines equals the velocity of light. In actual practice because of the resistance and conductance (leakance) of the lines the velocity of the travelling wave is slightly less than this. Normally a velocity of approximately 250 m/μ sec is assumed.

The velocity of these waves over the cables will be smaller than over the overhead lines because of the; Since $\varepsilon = \varepsilon_0\varepsilon_r$ for overhead lines $\varepsilon_r = 1$ whereas for cables where the conductor permittivity term in the denominator is surrounded by some dielectric material for which $\varepsilon_r > 1$, the term ε is greater for cables than for O/H lines and therefore the velocity of the waves over the cables is smaller than over the overhead lines.

Behavior of Different Lines to the Travelling Waves

Open End Line

Consider a line with the receiving end open-circuited as shown in Fig.



When switch S is closed, a voltage and current wave of magnitudes V and I respectively travel towards the open end. These waves are related by the equation:

$$\frac{V}{I} = Z$$

Where Z is the characteristic impedance of the line. Consider the last element dx of the line, because, it is here where the wave is going to see a change in impedance, an impedance different from Z (infinite impedance as the line is open-ended).

The electromagnetic energy stored by the element dx is given by $\frac{1}{2}LdxI^2$ and electrostatic energy in the element dx, $\frac{1}{2}CdxV^2$. Since the current at the open end is zero, the electromagnetic energy vanishes and is transformed into electrostatic energy. As a result, let the change in voltage be e;

$\frac{1}{2}LdxI^2 = \frac{1}{2}Cdxe^2$

Or, $\left(\frac{e}{I}\right)^2 = \frac{L}{C}$

Or, e = IZ = V

This means the potential of the open end is raised by V volts; therefore, the total potential of the open end when the wave reaches this end is $V + V = 2V$.

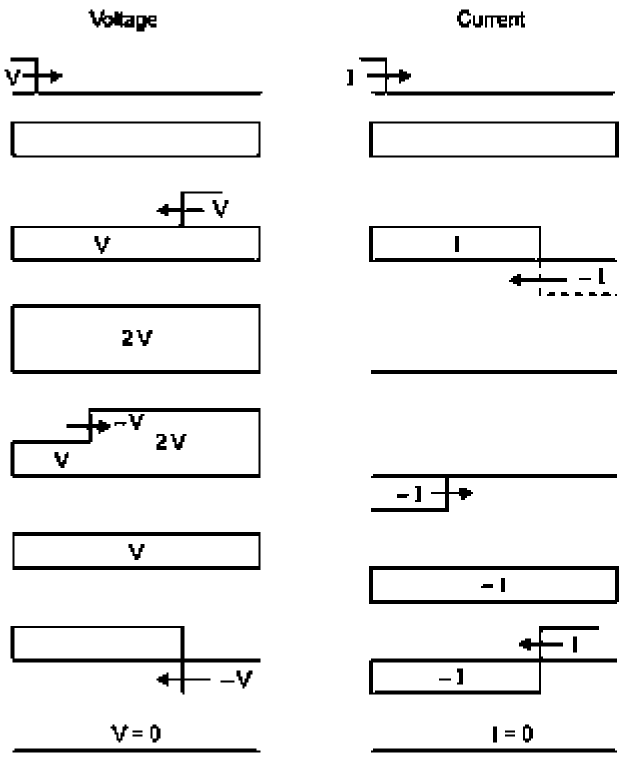
The wave that starts travelling over the line when the switch S is closed, could be considered as the incident wave and after the wave reaches the open end, the rise in potential V could be considered due to a wave which is reflected at the open end and actual voltage at the open end could be considered as the refracted or transmitted wave and is thus

Refracted wave = Incident wave + Reflected wave

We have seen that for an open-end line a travelling wave is reflected back with positive sign and coefficient of reflection as unity.

Let us see now about the current wave.

As soon as the incident current wave I reaches the open end, the current at the open end is zero, this could be explained by saying that a current wave of I magnitude travels back over the transmission line. This means for an open-end line; a current wave is reflected with negative sign and coefficient of reflection unity. The variation of current and voltage waves over the line is explained in Fig below.

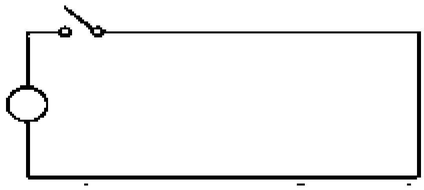


Variation of Voltage and Current in an Open-ended line

After the voltage and current waves are reflected back from the open end, they reach the source end, the voltage over the line becomes 2V and the current is zero. The voltage at source end cannot be more than the source voltage V, therefore, a voltage wave of –V and current wave of –I is reflected back into the line. It can be seen that after the waves have travelled through a distance of 4l where l is the length of the line, they would have wiped out both the current and voltage waves, leaving the line momentarily in its original state. The above cycle repeats itself.

Short Circuited Line

Consider the line with receiving end short-circuited as shown in Fig.



When switch S is closed, a voltage wave of magnitude V and current wave of magnitude I start travelling towards the shorted end. Consider again the last element dx where the electrostatic energy stored by the element is $\frac{1}{2}CdxV^2$ and electromagnetic energy $\frac{1}{2}LdxI^2$. Since the voltage at the shorted

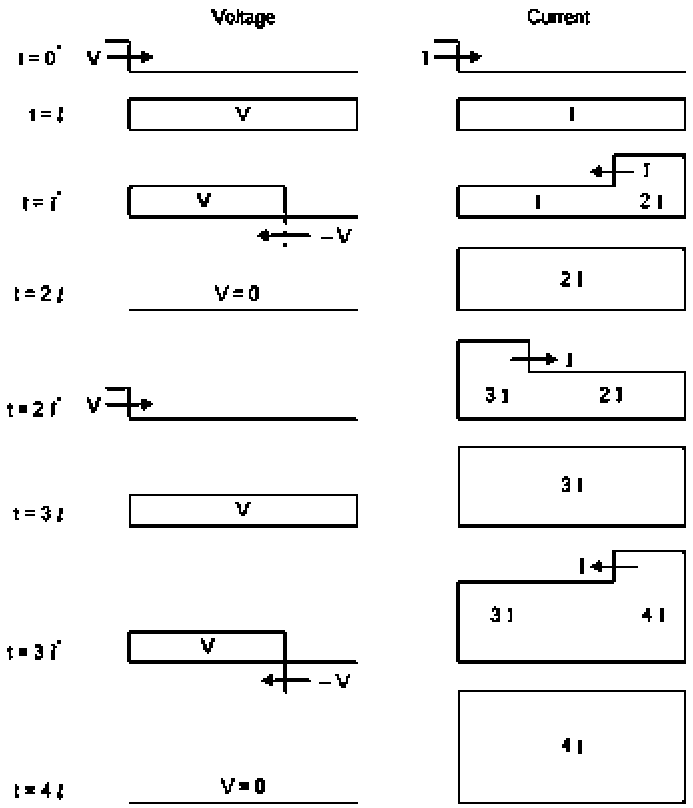
end is zero, the electrostatic energy vanishes and is transformed into electromagnetic energy. As a result, let the change in the current be *i*; then

$$\frac{1}{2}CdxV^2 = \frac{1}{2}Ldxi^2$$

Or, V = iZ

Or, i = $\frac{V}{Z} = I$

This means the increase in current is *I* amperes. As a result, the total current at the shorted end, when the current wave reaches the end is *(I + I) = 2I* A. This could be considered due to a reflected current wave of magnitude I amperes. Therefore, for a short-circuited end the current wave is reflected back with positive sign and coefficient of reflection as unity. Since the voltage at the shorted end is zero, a voltage wave of *–V* could be considered to have been reflected back into the line, i.e., the current wave in case of short-circuited end is reflected back with positive sign and with coefficient of reflection as unity, whereas the voltage wave is reflected back with negative sign and coefficient of reflection as in the variation of voltage and current over the line is explained in Fig.



Variation of Voltage and Current in a Short Ended Line

It is seen from above that the voltage wave periodically reduces to zero after it has travelled through a distance of twice the length of the line whereas after each reflection at either end the current is built up by an amount $V/Z_n=I$.

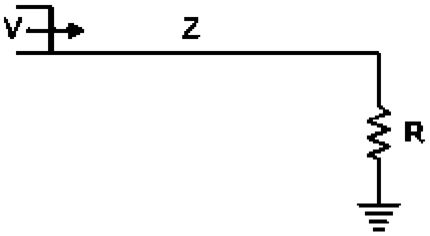
Theoretically, the reflections will be infinite and therefore, the current will reach infinite value. But practically in an actual system the current will be limited by the resistance of the line and the final value of the current will be $I' = V/R$, where R is the resistance of transmission line.

Line Terminated Through a Resistance

Let Z be the surge impedance of the line terminated through a resistance R. It has been seen in the previous sections that whatever be the value of the terminating impedance whether it is open or short circuited, one of the two voltage or current waves is reflected back with negative sign. Also, since the reflected wave travels along the overhead line or over the line along which the incident wave travelled, therefore, the following relation holds good for reflected voltage and current waves.

$I' = \frac{V'}{Z}$ where V' and I' are the reflected voltage and current waves.

Also, Refracted or transmitted wave = Incident wave + Reflected wave



Let V″ and I″ be the refracted voltage and current waves into the resistor R when the incident waves V and I reach the resistance R. The following relations hold good:

$$I = \frac{V}{Z}$$
$$I' = -\frac{V'}{Z}$$
$$I'' = \frac{V'''}{Z}$$

Since $I'' = I + I'$ and $V'' = V + V'$, using these relations, we have

$$\frac{V'''}{R} = \frac{V}{Z} - \frac{V'}{Z} = \frac{V}{Z} - \frac{V''' - V}{Z} = \frac{2V}{Z} - \frac{V'''}{Z} \qquad \ldots\ldots (1)$$

or

$$V''' = \frac{2VR}{Z + R} \qquad \ldots\ldots (2)$$

and current $$I'' = \frac{2V}{R+Z} = \frac{V}{Z} \cdot \frac{2Z}{R+Z} = I \cdot \frac{2Z}{R+Z} \qquad \ldots\ldots (3)$$

Similarly substituting for V'' in terms of $(V + V')$, equation (1) becomes

$$\frac{V + V'}{R} = \frac{V}{Z} - \frac{V'}{Z}$$

or

$$V' = V\,\frac{R - Z}{R + Z} \qquad \ldots\ldots (4)$$

and

$$I' = -\frac{V'}{Z} = -\frac{V}{Z}\,\frac{(R - Z)}{R + Z} \qquad \ldots\ldots (5)$$

From the relations above, the coefficient of refraction for current waves

$$= \frac{2Z}{R + Z}$$

and for voltage waves $$= \frac{2R}{R + Z}$$

Similarly, the coefficient of reflection for current waves

$$= -\frac{R-Z}{R+Z}$$

and for voltage waves

$$= +\frac{R-Z}{R+Z}$$

Sometimes, Greek alphabet Γ is used to denote the coefficient of reflection. Then, coefficient of refraction (transmission) is $1+\Gamma$.

Summarizing general expressions,

$$\text{(i) for current wave, } \Gamma = -\frac{R-Z}{R+Z}, \quad 1+\Gamma = \frac{2Z}{R+Z} \longrightarrow \Gamma = -\frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad 1+\Gamma = -\frac{2Z_1}{Z_2 + Z_1}$$

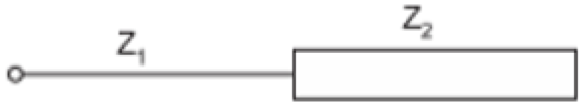
or

$$\text{(ii) for voltage wave, } \Gamma = +\frac{R-Z}{R+Z}, \quad 1+\Gamma = \frac{2R}{R+Z} \longrightarrow \Gamma = +\frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad 1+\Gamma = \frac{2Z_2}{Z_2 + Z_1}$$

Line Connected to a Cable

A wave travels over the line and enters the cable. Since the wave looks into a different impedance, it suffers reflection and refraction at the junction and the refracted voltage wave is given by

$$V''' = V\frac{2Z_2}{Z_1 + Z_2}$$



The other waves can be obtained by using the relations derived earlier. The impedance of the overhead line and cable are approximately 400 ohms and 40 ohms respectively. With these values it can be seen that the voltage entering the cable will be

$$V''' = V \cdot \frac{2 \times 40}{40 + 400} = \frac{2}{11} V$$

i.e., it is about 20% of the incident voltage V. It is for this reason that an overhead line is terminated near a station by connecting the station equipment to the overhead line through a short length of underground cable.

Besides the reduction in the magnitude of the voltage wave, the steepness is also reduced because of the capacitance of the cable.

The reduction in steepness is very important because this is one of the factors for reducing the voltage distribution along the windings of the equipment. While connecting the overhead line to a station equipment through a cable it is important to note that the length of the cable should not be very short (should not be shorter than the expected length of the wave) otherwise successive reflections at the junction may result in piling up of voltage and the voltage at the junction may reach the incident voltage.

Reflection and Refraction at a T – junction

A voltage wave V is travelling over the line with surge impedance Z_1 as shown in Fig. When it reaches the junction, it looks a change in impedance and, therefore, suffers reflection and refraction. Let V_2'', I_2'' and V_3'', I_3'' be the voltages and currents in the lines having surge impedances Z_2 and Z_3 respectively.

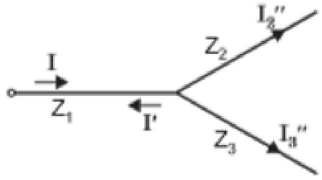
Since Z_2 and Z_3 form a parallel path as far as the surge wave is concerned, $V_2'' = V_3'' = V''$. Therefore, the following relations hold good.

$$V + V' = V''$$

$$I = \frac{V}{Z_1},\ I' = -\frac{V'}{Z_1}$$

$$I_2'' = \frac{V''}{Z_2} \quad \text{and} \quad I_3'' = \frac{V''}{Z_3} \qquad \ldots\ldots (1)$$

and $$I + I' = I_2'' + I_3'' \qquad \ldots\ldots (2)$$



A Bifurcated Line

From Eqns. (1) and (2)

$$\frac{V}{Z_1} - \frac{V'}{Z_1} = \frac{V''}{Z_2} + \frac{V''}{Z_3}$$

Substituting for $V' = V'' - V$,

$$\frac{V}{Z_1} - \frac{V'' - V}{Z_1} = \frac{V''}{Z_2} + \frac{V''}{Z_3}$$

$$\frac{2V}{Z_1} = V''\left(\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3}\right)$$

or $$V'' = \frac{2V/Z_1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3}} \qquad \ldots\ldots (3)$$

Similarly, other quantities can be derived.

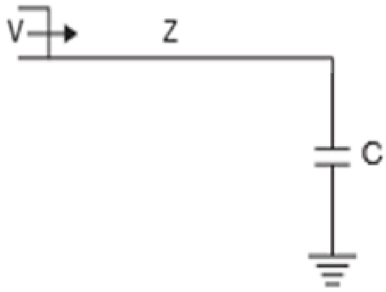
Line Terminated through a Capacitance (as a Compensating device)

We consider here that a surge travels over the line of surge impedance Z and is incident on the capacitor as shown in Fig. We are interested in finding out the voltage across the capacitor i.e., the refracted voltage. The refracted voltage, using equation derived previously is;

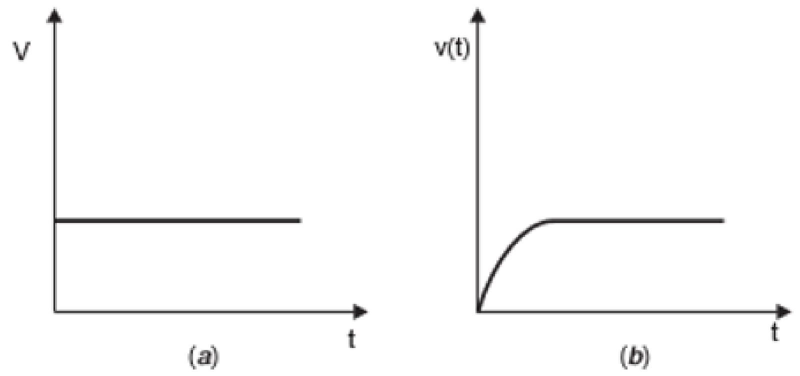
$$V''(s) = \frac{2 \times 1/Cs}{Z + 1/Cs} \cdot \frac{V}{s} = \frac{2V}{s}\,\frac{1}{ZCs + 1}$$

$$= \frac{2V}{s} \cdot \frac{1/ZC}{s + 1/ZC} = 2V\left[\frac{1}{s} - \frac{1}{s + 1/ZC}\right]$$

$$v''(t) = 2V[1 - e^{-t/ZC}]$$



The variation of voltage is shown in Fig. Since terminating impedance is not a transmission line, therefore, *V''(s)* is not a travelling wave but it is the voltage across the capacitor C.

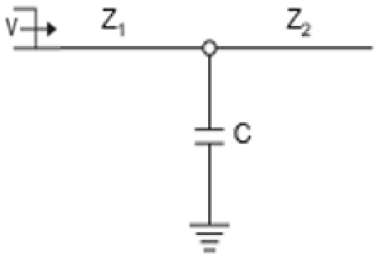


(a) Incident voltage **(b) Voltage across capacitor**

Capacitor Connection at a T

The voltage across capacitor is given by the equation

$$V''(s) = \frac{2V/Z_1 s}{\frac{1}{Z_1}+\frac{1}{Z_2}+Cs} = \frac{2VZ_2}{s}\cdot\frac{(1/Z_1Z_2C)}{\frac{Z_1+Z_2}{Z_1Z_2C}+s} = \frac{2V}{sZ_1C}\cdot\frac{1}{s+\frac{Z_1Z_2}{Z_1Z_2C}}$$



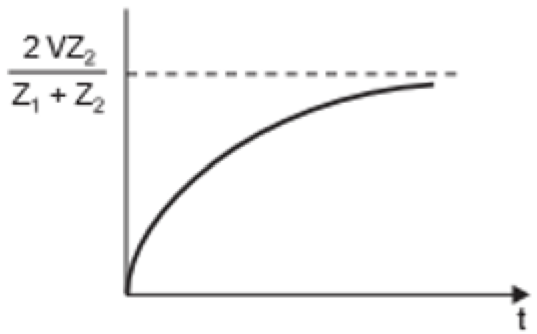
Let $\frac{Z_1+Z_2}{Z_1Z_2C} = \alpha;$ then $V''(s) = \frac{2V}{s}\cdot\frac{1/Z_1C}{s+\alpha}$

or $V''(s) = \frac{2V}{s}\cdot\frac{Z_2}{Z_1+Z_2}\cdot\frac{(Z_1+Z_2)/Z_1Z_2C}{(s+\alpha)}$

$$= \frac{2V}{s}\cdot\frac{Z_2}{Z_1+Z_2}\cdot\frac{\alpha}{s+\alpha} = \frac{2VZ_2}{Z_1+Z_2}\left[\frac{1}{s}-\frac{1}{s+\alpha}\right]$$

or $$v''(t) = \frac{2V\,.\,Z_2}{Z_1+Z_2}\left[1-\exp\left(-\frac{Z_1+Z_2}{Z_1Z_2C}\,t\right)\right]$$

The variation of the wave is as shown in Figure below.



Substation Transformer

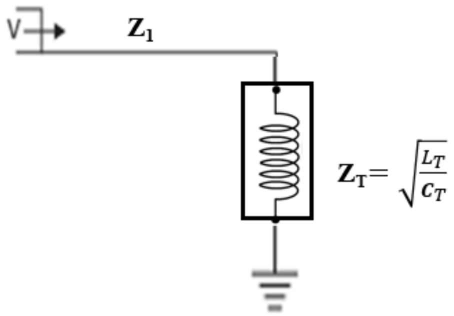
$V'' = \frac{2ZT}{Z1+ZT}$

Practically, $ZT \gg Z1$

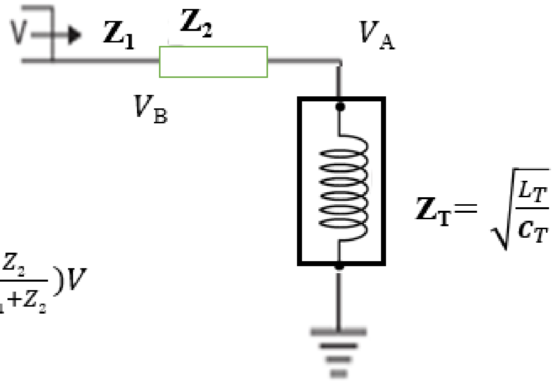
(Normally, Z_1= 400 Ω and Z_T= 2,000 Ω ~ 4,000 Ω) (Taking Z_T= 4,000 Ω)

$V'' = \frac{2\times4000}{400+4000}\ V\ = \frac{8000}{4400}\ V$ = 1.9 V ≈ **2** V

Though the transformer is connected, it is equivalent to an open-ended line. Surge gets doubled at the transformer termination.



Line, Cable and Substation Transformer



$$V_B = \frac{2Z_2}{Z_1 + Z_2} V$$

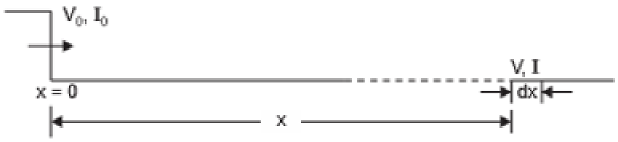
$$V_A = \frac{2Z_T}{Z_2 + Z_T} V_B \quad = \frac{2Z_T}{Z_2+Z_T}\ \frac{2Z_2}{Z_1+Z_2}\ V \quad = 2\left(\frac{2Z_T}{Z_2+Z_T}\ \frac{Z_2}{Z_1+Z_2}\right)V$$

Normally , $Z_2 \ll Z_1$ because of the high capacitance of the cable.

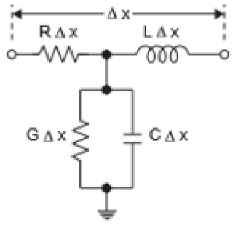
So, $\frac{Z_2}{Z_1+Z_2} \ll 1$

Attenuation of Travelling Waves

Let R, L, C and G be the resistance, inductance, capacitance and conductance respectively per unit length of a line as shown in Fig. Let the value of voltage and current waves at x = 0 be V_0 and I_0. Our objective is to find the values of voltage and current waves when they have travelled through a distance of x units over the overhead line. Let the time taken be t units when voltage and current waves are V and I respectively. To travel a distance of dx, let the time taken be dt. The equivalent circuit for the differential length dx of the line is shown in another figure.



Travelling Wave on a Lossy Line



Differential Element of Transmission Line

The power loss in the differential element is

$$dp = I^2R\,dx + V^2G\,dx \qquad \ldots\ldots (1)$$

Also, power at a distance *x*,

$$VI = p = I^2Z_n$$

Differential power,

$$dp = -\,2IZ_n dI \qquad \ldots\ldots (2)$$

where Z_n is the natural impedance of the line. Here negative sign has been assigned as there is reduction in power as the wave travels with time.

Equating the equation (1) and (2),

$$-\,2IZ_n dI = I^2Rdx + V^2Gdx$$
$$= I^2Rdx + I^2Z_n^2Gdx$$

or $$dI = -\frac{I(R + GZ_n^2)}{2Z_n}\,dx$$

or $$\frac{dI}{I} = -\frac{(R + GZ_n^2)}{2Z_n}\,dx$$

or $$\ln I = -\frac{(R + GZ_n^2)}{2Z_n}\,x + A$$

At $x = 0$, $I = I_0$, $\therefore$ $A = \ln I_0$

or $$\ln\frac{I}{I_0} = -\frac{R + GZ_n^2}{2Z_n}\,x = -\,\alpha x \text{ (say)}$$

where $$a = \frac{R + GZ_n^2}{2Z_n}.$$

$$\therefore \qquad I = I_0e^{-\alpha x}.$$

Similarly it can be proved that $V = V_0e^{-\alpha x}$.

This shows that the current and voltage waves get attenuated exponentially as they travel over the line and the magnitude of attenuation depends upon the parameters of the line.

The value of resistance depends not only on the size of the conductors but also on the shape and length of the waves. An empirical relation due to Foust and Menger takes into account the shape and length of the wave for calculating the voltage and current at any point on the line after it has travelled through a distance x unit and is given as;

$$V = \frac{V_0}{1 + KxV_0}$$

where x is in kms, V and V_0 are in kV and K is the attenuation constant, of value

K = 0.00037 for chopped waves

= 0.

UNIT 6 PROTECTION AGAINST HIGH VOLTAGE SURGE

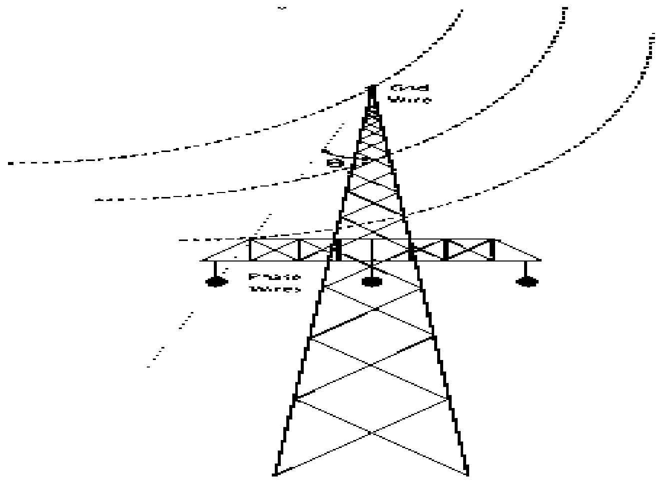
Protection Against Lightning

Different methods are employed for the protection of overhead lines against the over voltages caused by lightning.

- Applying earth wire above the line
- Applying ground rods and counter-poise-wires
- Using surge arrestors

Earth wire or shielding wire

It is a galvanized iron wire which proceeds parallel to the and always above the transmission line. The angle 'θ', called **shielding angle** or **protection angle** is the angle between the lines joining the outermost conductor and the top of the tower with the vertical. The spacing between conductor and ground wires as well as the spacing between line and tower is fixed to maintain the desired shielding angle.



Ground Rods

It is made of galvanized iron or copper steel, connected to the legs of the tower at one end and buried. General dimensions of the rods are 15 mm diameter and 3 m length. Number and the depth of the rods depends upon the desired tower footing resistance. The space between the rods is to be maintained at 5 m.

Alternately, counterpoise wires are used. Compositions of counterpoise wires is the same as the driven rods. 50 – 100 m long rods are buried to the depth of 1 m. These are aligned parallel to the line conductors and connected to the legs of the tower. Counterpoise is more effective than the vertically driven rods. Several counterpoise can be connected in parallel for reduced resistance. Depth doesn't have any effect on resistance in this case, depth is needed only to prevent the theft of rods. Counterpoise is costlier than the vertical driven rods.

The source impedance of the lightning channels is not known exactly, but it is estimated to be about 1000 to 3000 Ω. The surge impedance of O/H lines is 300 to 500 Ω, ground wires is 100 to 150 Ω and towers 10 to 50 Ω. So, the value of Z/Z_0 will usually be less than 0.1 and can be neglected.

Hence, the voltage rises of lines due to the lightning strike can be approximated to

$V=I_0Z$.

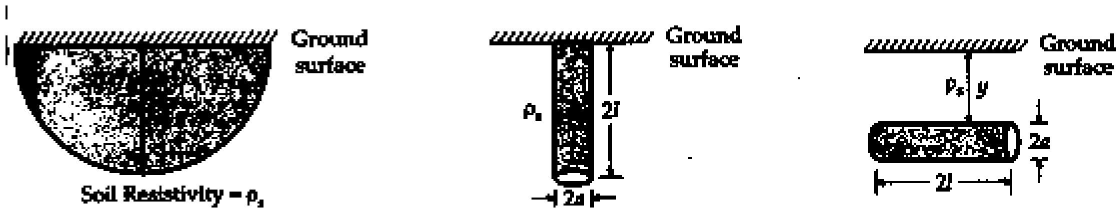
It is obvious that if Z is reduced, V will also be reduced.

Z is proportional to the tower footing resistance R_{tf}, which depends on;

a) Type of electrodes
b) Resistivity of soil

The most commonly used electrode shapes are;

i) the hemisphere ii) vertical driven rods iii) counterpoise wires



i) the hemisphere ii) vertical driven rods iii) counterpoise wires

Figure: Most Commonly used Electrode Shapes for Tower Footing

Soil resistivity depends upon the types and conditions of soil.

Sea Water: 1 Ω-m

Moist Soil: 10 Ω-m

Loose Soil and Clay: 100 Ω-m

Rock: 1,000 Ω-m

The expressions for various types of electrodes resistances are:

i) Hemisphere; $\frac{\rho S}{2\pi R}$ ii) Vertical-driven Rod; $\frac{\rho S}{2\pi l}\log\left(\frac{2l}{a}\right)$ iii) Counter-poise-wire; $\frac{\rho S}{2\pi l}\ln\left(\frac{2l^2}{ay}\right)$

Lightning Arresters

These are the devices which can discharge the lightning overvoltage and are used at sub-stations and at line terminations. They are usually mounted at line end at the nearest point to the sub-station. They have a flashover voltage lower than all other equipment including insulators. They are capable of discharging 10~20 kA of long duration (e.g.100/2500 µS surge) surges and 100~250 kA of short duration surges (1/50 µS surge)

Basic requirement:

1) It shouldn't pass any current at normal power frequency conditions.

2) Should breakdown as soon a possible under lightning conditions.

3) It should protect the intended equipment and also should discharge the surge without damaging itself.

4) It shouldn't allow the power frequency follow-on current to flow after the surge is removed.

Operating principle

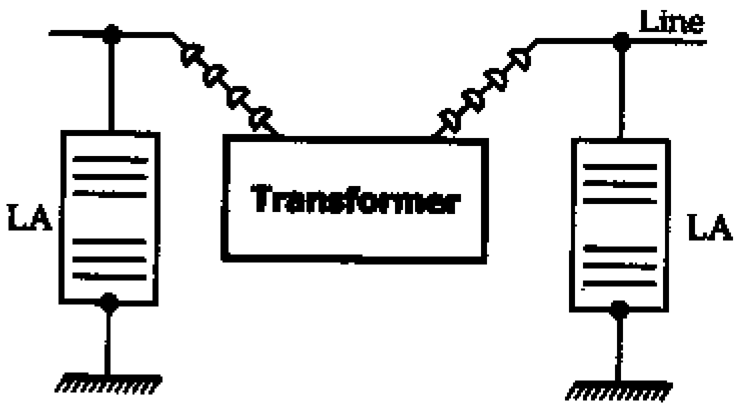
When the surge wave travelling along OH-line comes to the arrester, there is break down inside it and the current flows through it. The voltage at which the L.A. breaks down is called the impulse-spark-over-voltage. The surge is then diverted to Earth. The main part of any LA is a non-linear resistive element. These elements are stacked one over the other into two or three sections. In some case they may be separated by spark gaps. The entire assembly is housed in water tight porcelain or polymer housing. Non-linear resistors offer high resistance to normal power frequency (low) voltage and low resistance to high voltage surges. The volt-ampere characteristics of the non-linear resistor element:

$I_d = kV^a$

where; I_d= discharge current

V= applied voltage across the element

k, a= constants depending on material and dimensions



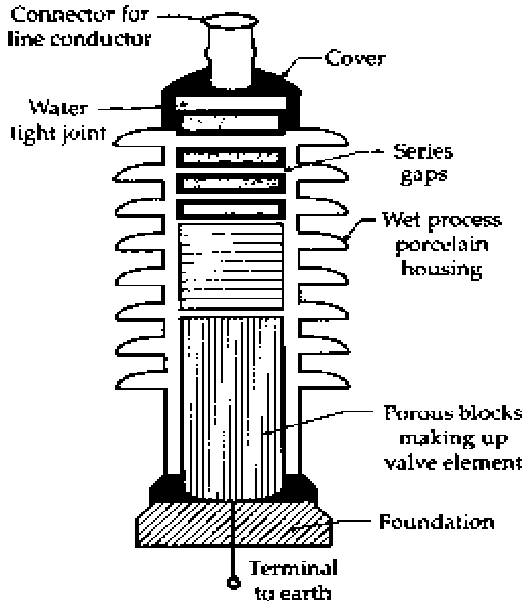
Location of L.A:

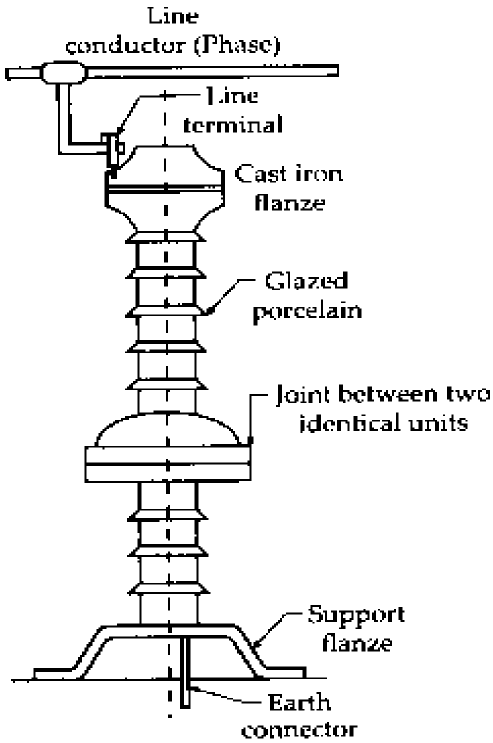
Normal practice is to place the LA as close as possible to the equipment or the line to be protected. By doing so the chances of surge entering the equipment is reduced. One example is shown in the figure above. Surge arresters are necessarily installed in the incoming lines near the sub-station, near the transformers and near rotating machines.

Types: Generally, two types of LA are most commonly used.

Gap Type LA

It consists of non-linear resistors in series with spark gaps which act as fast switches. Non-linear resistor elements generally made up of silicon carbide (SiC). During the normal voltage, LA does not conduct. When surge travelling along the line comes to the arrester, the gap breaks down and the surge is diverted to the earth. After a few micro-seconds the surge vanishes and normal power frequency voltage is set up across the arrester. Therefore, the arc current reduces. The voltage is not sufficient to maintain the arc and the current flowing to the earth is automatically interrupted and normal condition is restored.

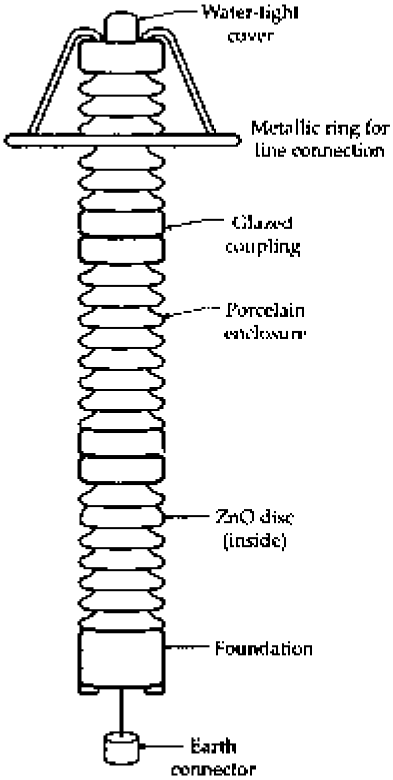




Metal Oxide LA

It uses of metal oxides (Z_nO, Bi_2O_3, Co_2O_3) as the non-linear resistor. Z_nO is the most commonly used. The arrester comprises of numbers of solid metal oxide disc. This disc are arranged one by one to form a cylindrical stack. The number of discs used per lightning arrester depends upon the voltage rating of the system. This stack is kept inside a cylindrical housing of polymer or porcelain. Initially the leakage current across the arrester is in the range of µA. Beyond a certain voltage level, leakage current through the arrester element starts increasing very rapidly. This voltage level is referred as reference voltage and the current at reference voltage is known as reference current. Sudden draining of huge current through lightning arrester just beyond reference voltage level, prevents the system from transient over voltage stress. The voltage-current relation in a metal oxide block highly depends upon temperature. Metal oxide block has negative temperature co-efficient.

The leakage current through the arrester generates heat. This heat should be dissipated properly otherwise the temperature of the LA may rise further increasing the leakage current. Because of this, the proper thermal design of surge arrester housing plays an important role. There is a critical temperature depending upon the voltage rating of the metal oxide block beyond which joule heat generated in the block cannot be dissipated at required rate and which finally leads to thermal runaway of lightning arrester.



External Appearance of Porcelain Housing Metal Oxide LA

Expulsion Type LA

Expulsion type lightning arrester is also known as a protector tube. It consists of – (i) a tube made of fibre which is very effective gas-evolving material (ii) an isolating spark gap (or external series gap) and (iii) an interrupting spark gap inside the fibre tube.

During operation arc due to the impulse spark-over inside the fibrous tube causes some fibrous material of the tube volatized in the form of gas, which is expelled through a vent from the bottom of the tube, thus extinguishing the arc just like in circuit breakers. Since the gases generated have to be expelled, one of the electrode is hollow and the diverter is open at its lower end.

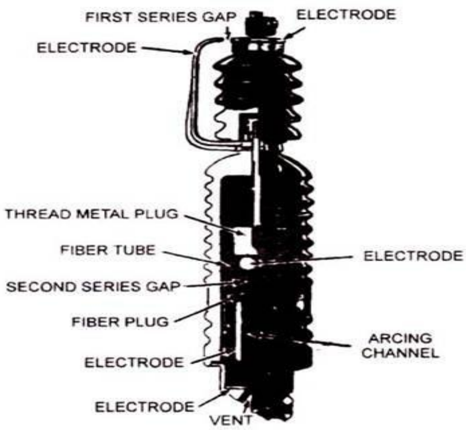
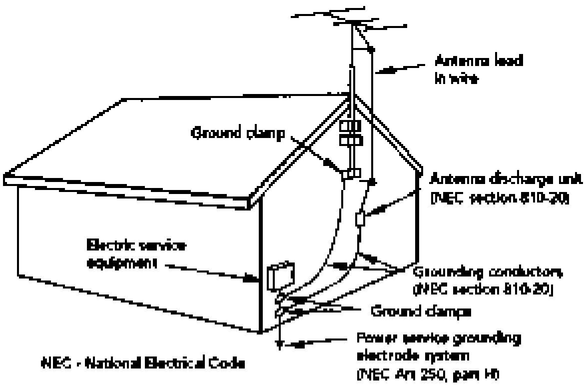


Fig. 9.26. ***Expulsion Type Lightning Arrester***

Expulsion type arrester is an improvement over the rod gap in that it seals the flow of power frequency follow current. Its use is normally restricted to circuits in which the possible range of power current magnitude following a spark-over is not more than about three to one, since an excessive current may cause bursting of tube while a small current may not produce sufficient pressure to extinguish the arc.

Grounding Mast

Codes in most of the countries require that the antenna mast and the coaxial cable be bonded to the building's ground electrode system. The ground for the mast should be as direct and short as possible, with minimal bends. The coaxial cable that comes from the antenna also needs to be bonded to the GES. This is accomplished by using a ground block located as close as possible to where the coaxial cable enters the building.

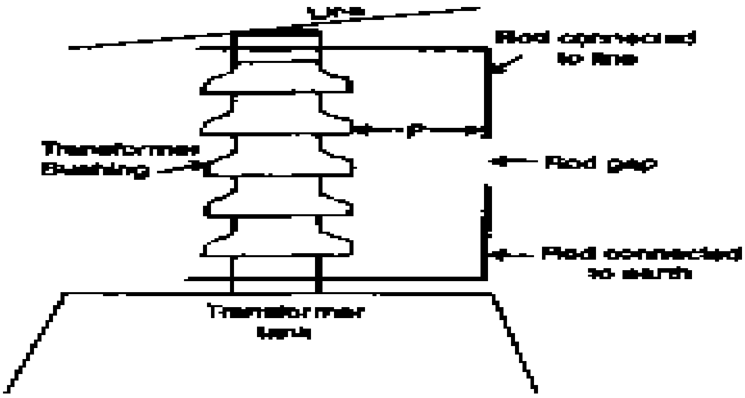


Surge Protection

An overhead earth wire provides considerable protection against direct strikes. They also reduce induced over-voltages. However, they do not provide protection against surges that may still reach the terminal equipment. Such protection may either be done by diverting the major part of the energy of the surge to earth (surge diverters), or by modifying the waveform to make it less harmful (surge modifiers). The insertion of a short length of cable between an overhead line and a terminal equipment is the commonest form of surge modifier.

Spark gaps (rod gaps) for surge protection

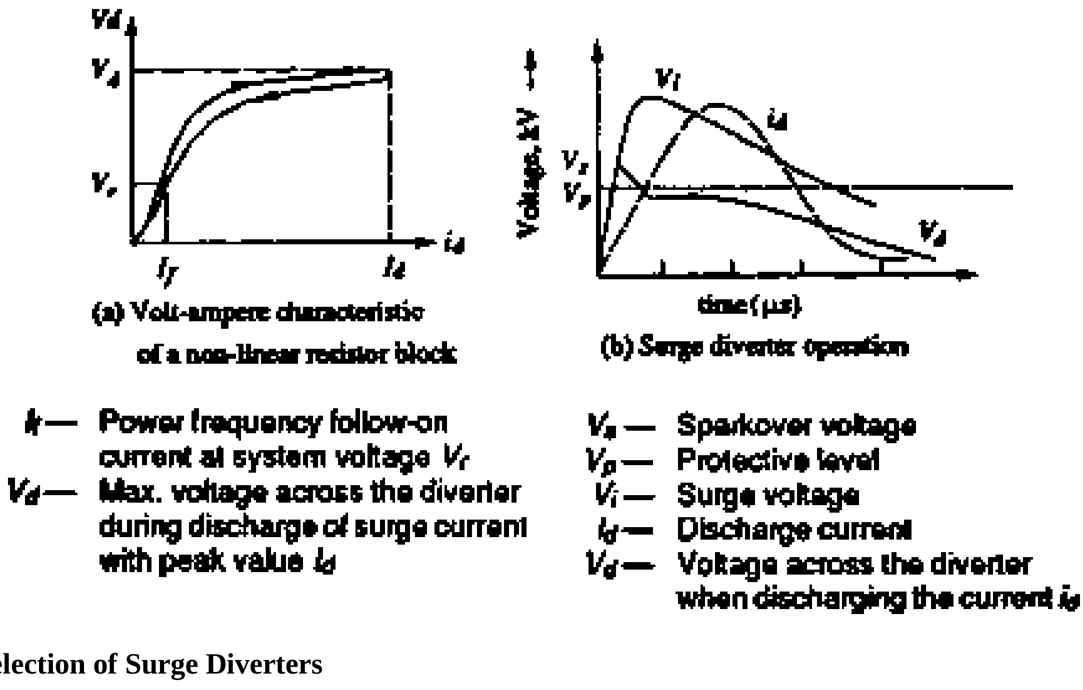
The simplest and cheapest form of protection is the spark gap. The selected gap spacing should not only be capable of withstanding the highest normal power frequency voltage but should flash-over when over-voltages occur, protecting the equipment.



Rod gaps are simple and cheap devices but do not meet all the requirements of a protective device. Moreover, their flashover characteristics depend on the atmospheric conditions, polarity of the wave, and waveshape. Also, it may give rise to very steep impulse waves on the transformer windings as chopped waves, because no current limiting resistance is used. Chopped impulse waves may lead to the destruction of the transformer turn to turn insulation. But still, rod gaps provide reasonable protection where lightning surge levels are low, and steep fronted surges are controlled by overhead ground wires.

Surge Diverters

Surge diverters (or surge arrestors) generally consist of one or more spark gaps in series, together with one or more non-linear resistors in series. Silicon Carbide (SiC) was the material most often used in these nonlinear resistor surge diverters. However, Zinc Oxide (ZnO) is being used in most modern-day surge diverters on account of its superior volt-ampere characteristic. In fact, the ZnO arrestor is often used gapless, as its normal follow current is negligibly small. When a surge voltage is applied to the surge diverter, it breaks down giving the discharge current and maintains a voltage across it Thus, it provides a protection to the apparatus to be protected above the protective level.



Selection of Surge Diverters

Surge diverters for a particular purpose are selected as follows.

(a) Rated Voltage: The designated maximum permissible r.m.s. value of power frequency voltage between line and earth terminals. This is generally selected corresponding to 80% of the system phase-to-phase voltage for effectively earthed systems and corresponding to 100% of the system phase-to-phase voltage for non-effectively earthed systems. [Note: A surge diverter of a higher rating may sometimes have to be chosen if some of the other required criteria are not satisfied by this diverter].

(b) Discharge Current: The surge current that flows through the surge diverter after spark over.

Nominal discharge current: This is the discharge current having a designated crest value and waveshape, which is used to classify a surge diverter with respect to durability and protective characteristics. The standard waveform for the discharge current is taken as 8/20 µs.

The nominal value of discharge current is selected from the standard values 10 kA (station type), 5 kA (intermediate line type), 2.5 kA (distribution type) and 1.5 kA (secondary type), depending on the application. The highest ratings are used for the protection of major power stations, while the lowest ratings are used in rural distribution systems. The above nominal discharge currents are chosen based on statistical investigations which have shown that surge diverter currents at the station has the following characteristic.

99 % of discharge currents are less than 10 kA

95 % of discharge currents are less than 5 kA

90 % of discharge currents are less than 3 kA

70 % of discharge currents are less than 1 kA

50 % of discharge currents are less than 0.5 kA

(c) Discharge Voltage (or Residual voltage): The Discharge voltage is the voltage that appears between the line and earth terminals of the surge diverter during the passage of discharge currents. The discharge voltage of the selected arrestor should be below the BIL of the protected equipment by a suitable margin (generally selected between 15% and 25%). The discharge voltage of an arrestor at nominal discharge current is not a constant, but also depends on the rate of rise of the current and the waveshape. Typically, an increase of the rate of rise from 1 kA/µs to 5 kA/µs would increase the discharge voltage by only about 35 %.

The dependence of the discharge voltage on the discharge current is also small. Typically, an increase of discharge current from 5 kA to 10 kA would increase the discharge voltage by about 15% for Silicon Carbide arrestors and by about 2% for Zinc Oxide arrestors. {The discharge voltage is more often referred to as the residual discharge voltage].

(d) Power frequency spark over voltage: The power frequency spark over voltage is the r.m.s. value of the lowest power frequency voltage, applied between the line and earth terminals of a surge diverter, which causes spark-over of all the series gaps. The power frequency spark over voltage should generally be greater than about 1.5 times the rated voltage of the arrestor, to prevent unnecessary sparkover during normal switching operations.

e) Impulse spark over voltage: The impulse spark over voltage is the highest value of voltage attained during an impulse of a given waveshape and polarity, applied between the line and earth terminals of a surge diverter prior to the flow of discharge current. The impulse spark over voltage is not a constant but is dependent on the duration of application. Thus, it is common to define a wave front impulse sparkover voltage in addition to the impulse spark-over voltage.

Good designs aim to keep (i) the peak discharge residual voltage, (ii) the maximum impulse sparkover voltage and (iii) the maximum wave front impulse sparkover voltage reasonably close to each other.

Arrestor Rating kV rms	Minimum Power frequency withstand	Maximum Impulse Spark-over voltage (1.2/50 μs) kV crest	Maximum Residual Voltage kV crest	Maximum Wavefront Sparkover Voltage kV crest
36	1.5 times rated voltage	130	133	150
50		180	184	207
60		216	221	250
75		270	276	310

Lightning Arrester

A lightning arrester is a device used on electric power systems and telecommunication systems to protect the insulation and conductors of the system from the damaging effects of lightning. The typical lightning arrester has a high-voltage terminal and a ground terminal. When a lightning surge or switching surge travels along the power line to the arrester, the current from the surge is diverted through the arrester, in most cases to earth.

Calculations of Lightning Arrester

The volt-ampere characteristics of the resistance element inside a lightning arrester is given by,

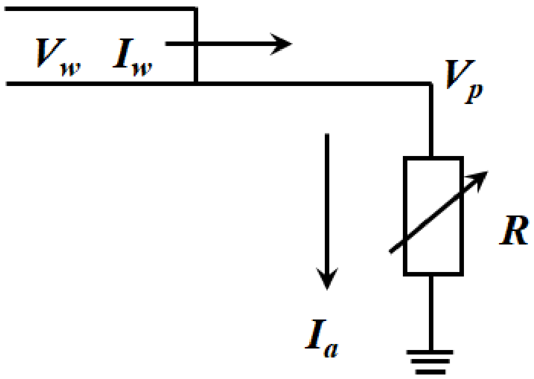
$I=kV^a$

Where, I= discharge current

V= applied voltage across the element

k, a= constants depending on material and dimensions

When a surge voltage V_w is applied to the surge arrester, it breaks down giving the discharge current I_a and maintains a voltage V_p across it.



With the arrester connected, the current through it is given by,

$$I_a = (2V_w-V_p)/Z$$

The maximum value the travelling wave-voltage V_w can reach is the flashover voltage of the line insulation. Also, it is assumed that V_p stays fairly constant at all current values discharged by the arrester.

Voltage across Equipment Protected by Arrester

In ideal case, the arrester must be located adjacent to the transformer or shunt reactor. In practice, however, there may be length of the line between the two extending to 20 to 40 m. This results in a slightly higher voltage across the equipment due to repeated reflections. The high inductance of a transformer or reactor represents nearly an open-circuit to a surge.

The **excess voltage** experienced is given by an empirical equation and depends on the line length and the rate of rise of the voltage.

$\Delta V = (dV_w/dt) \cdot (l/150)$ kV

where, l = length of the line (between LA and equipment) in m

dV_w/dt = steepness of wave fron in kV/μS of the incoming wave. This can be taken as approximately 500 kV/μS for lines with overhead ground wires and 1,000 kV/μS when a line conductor is hit.

Protection of Lines by Insulators

In a transmission line, an insulator serves two purposes;

- Mechanical support to the conductor
- Electrical separation between the line and the supporting structure (pole, tower)

Insulators are required to withstand not only the normal power frequency overvoltage but are required to withstand other high voltages too. Besides, they are required to operate in the worst conditions.

Transmission insulators come in various shapes and types, including individual or strings of disks, line posts or long rods. They are made of polymers, ceramic (glass and porcelain) each with different densities, tensile strengths and performing properties in adverse conditions.

Porcelain insulators: Strings of discs, post, bushing

Polymer insulators: long-rod, post type, bushing

Arcing horns

'Arcing horns' or 'arc horns' are projecting conductors used to protect insulators on high voltage lines from damage during flashovers. Flashover along the insulator can cause degradation of the insulator surface. The arc horns encourage the flashover to occur between themselves rather than across the insulators. Horns are normally paired on the either side of the insulator. Horns are frequently seen in HV O/H lines and transformer bushing. Horn gap is calculated according to the dielectric strength of air in the surrounding. Altitude is also considered while determining the horn gap. Normally, same value is used up to 1,000 m. above sea level. An increase of 1% per 100 m. is made after this altitude.

Corona Rings

Corona discharges only occur when the electric field (potential gradient) at the surface of conductors exceeds a critical value, the dielectric strength or *disruptive potential gradient* of air. It is roughly 30 kilovolts per centimeter, but varies with atmospheric pressure, so corona is more of a problem at high altitudes. The electric field at a conductor is greatest where the curvature is sharpest, and therefore corona discharge occurs first at sharp points, corners and edges. The terminals on very high voltage equipment are frequently designed with large diameter rounded shapes such as balls and toruses called *corona caps*, to suppress corona formation. However, some parts of high voltage circuits require hardware with exposed sharp edges or corners, such as the attachment points where wires or bus bars are connected to insulators. Corona rings are installed at these points to prevent corona formation.

The corona ring is electrically connected to the high voltage conductor, encircling the points where corona would form. Since the ring is at the same potential as the conductor, the presence of the ring reduces the potential gradient at the surface of the conductor greatly, below the disruptive potential gradient, so corona does not form on the metal points.

Grading Rings

Grading ring is a large metal ring surrounding the bottom unit of the insulator string and connected to the line. This introduces new capacitances between different metallic joints of the insulator string and the line. The overall effect is the improved string efficiency.

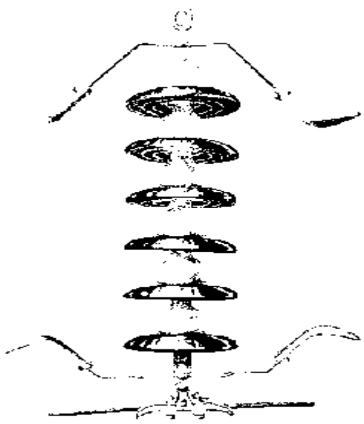


Fig: Arcing Horn

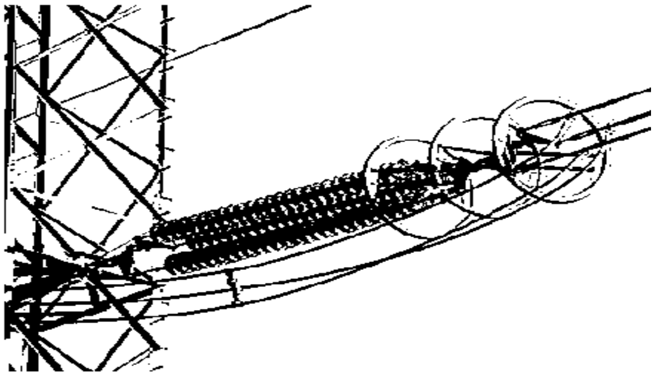
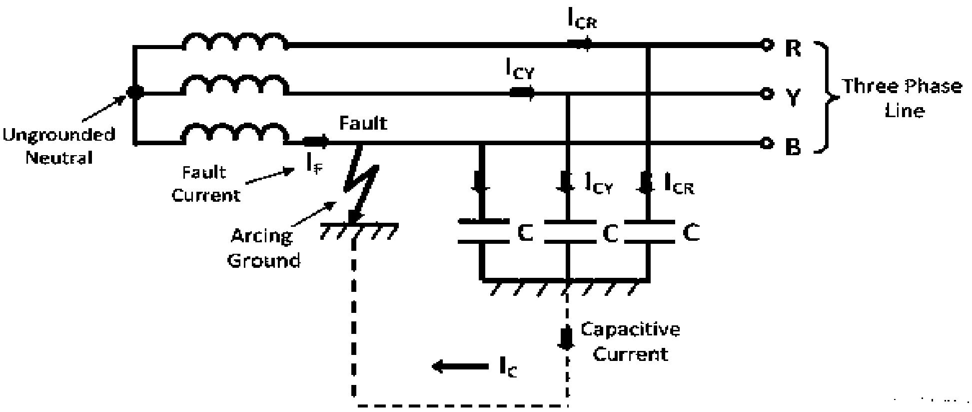


Fig: Grading Rings

Arcing Ground

Arcing ground is the surge, which is produced if the neutral is not connected to the earth. The phenomenon of arcing ground occurs in the ungrounded three-phase systems because of the flow of the capacitance current. The capacitive current is the current flow between the conductors when the voltage is applied to it. The voltage across the capacitances is known as the phase voltage. During the fault, the voltage across the capacitance reduces to zero in the faulted phase, while in the other phases the voltage is increased by the factor of $\sqrt{3}$ times.



Arcing Ground Phenomena

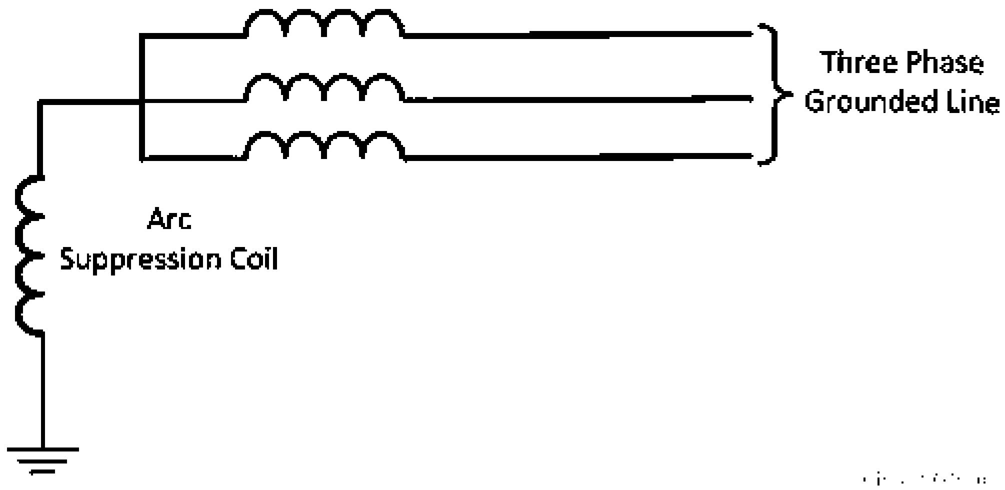
In a three-phase line, each phase has a capacitance on earth. When the fault occurs on any of the phases, then the capacitive fault current flows into the ground. If the fault current exceeds 4 – 5 amperes, then it is sufficient to maintain the arc in the ionised path of the fault, even though the fault has cleared itself.

The capacitive current over 4 to 5 ampere flows through the fault give rise to an arc in the ionised path of the fault. With the formation of the arc, the voltage across it becomes zero, and therefore the arc is extinguished. The potential of the fault current restored due to which the formation of a second arc takes places. The phenomenon of intermitting arcing is called the arcing grounding.

The alternating extinction and reignition of the charging current flowing in the arc build up the potential of the other two healthy conductors due to the setting of the high-frequency oscillations. The high-frequency oscillations are superimposed on the network and produce the surge voltage as high as six times the normal value. The overvoltage damages the healthy conductor at some other points of the system.

Eliminates Arcing Ground

The surge voltage due to arcing ground can remove by using the arc suppression coil or Peterson coil. The arc suppression coil has an iron cored tapped reactor connected in neutral to ground connection. The reactor of the arc suppression coil extinguishes the arcing ground by neutralising the capacitive current. The Peterson coil isolates the system, in which the healthy phases continue supplies power and avoid the complete shut down on the system till the fault was located and isolated.


Three Phase
Grounded Line
Arc
Suppression Coil

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