



ST. ANNE'S COLLEGE OF ENGINEERING AND TECHNOLOGY

Approved by AICTE, New Delhi. Affiliated to Anna University, Chennai

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ANGUCHETTYPALAYAM, PANRUTI – 607 106.

Department of Electrical and Electronics Engineering

EE3701 - HIGH VOLTAGE ENGINEERING

UNIT I - OVER VOLTAGES IN ELECTRICAL POWER SYSTEMS

1. Write short notes about Causes of over voltages and its effect on power system

It is essential for electrical power engineers to reduce the number of outages and preserve the continuity of service and electric supply. Therefore, it is necessary to direct attention towards the protection of transmission lines and power apparatus from the chief causes of overvoltages in electric systems, namely lightning overvoltages and switching overvoltages. Lightning overvoltage is a natural phenomenon, while switching overvoltages originate in the system itself by the connection and disconnection of circuit breaker contacts or due to initiation or interruption of faults. Switching overvoltages are highly damped short duration overvoltages. They are "temporary overvoltages" of power frequency or their harmonic frequencies either sustained or weakly damped and originate in switching and fault clearing processes in power systems. The magnitude of lightning voltages appearing on transmission lines does not depend on line design and hence lightning performance tends to improve with increasing insulation level that is with system voltage. On the other hand, switching overvoltages are proportional to operating voltage.

2. Write short notes about Charge Formation in the Clouds.

The factors that contribute to the formation or accumulation of charge in the clouds are too many and uncertain. But during thunderstorms, positive and negative charges become separated by the heavy air currents with ice crystals in the upper part and rain in the lower parts of the cloud. This charge separation depends on the height of the clouds, which range from 200 to 10,000 m, with their charge centre probably at a distance of about 300 to 2000m. Clouds may have a potential as high as 10^7 to 10^8 V with field gradients ranging from 100V/cm within the cloud to as high as 10 kV/cm at the initial discharge point. The energies associated with the cloud discharges can be as high as 250 kWh. It is believed that the upper regions of the cloud are usually positively charged, whereas the lower region and the base are predominantly negative except the local region, near the base and the head, which is positive. The maximum gradient reached at the ground level due to a charged cloud may be as high as 300 V/cm, while the fair weather gradients are about 1 V/cm.

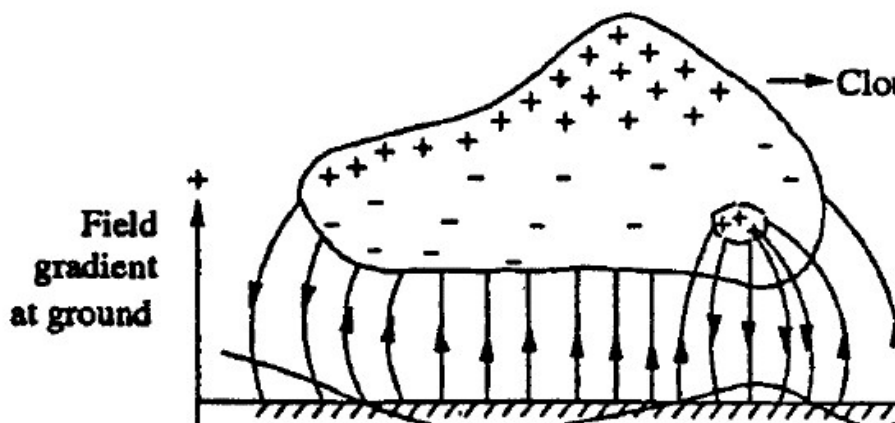


Fig. Probable field gradient near the ground corresponding to the probable charge distribution in a cloud

3. Explain the different theories of charge formation in clouds.

(May'11)

Simpson's theory

There are three essential regions in the cloud to be considered for charge formation.

Below region A, air currents travel above 800 cm/s, and no raindrops fall through.

In region A, air velocity is high enough to break the falling raindrops causing a positive charge spray in the cloud and negative charge in the air.

The spray is blown upwards, but as the velocity of air decreases, the positively charged water drops recombine with the larger drops and fall again. Thus region A, eventually becomes predominantly positively charged, while region B above it, becomes negatively charged by air currents. In the upper regions in the cloud, the temperature is low (below freezing point) and only ice crystals exist. The impact of air on these crystals makes them negatively charged, thus the distribution of the charge within the cloud becomes as shown in Fig.

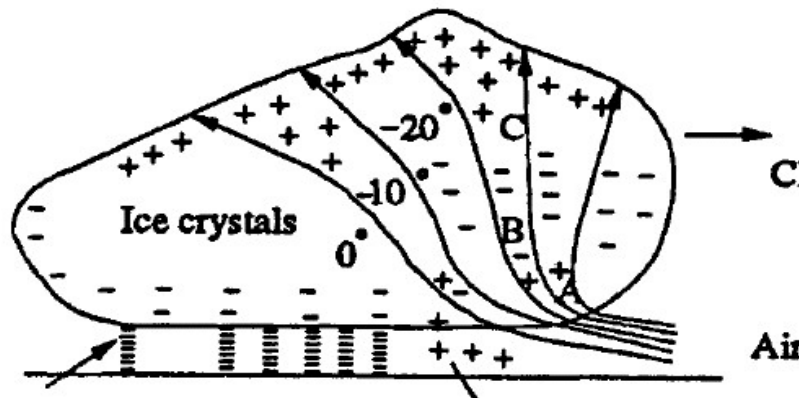


Fig. Cloud model according to Simpson's theory

Reynolds theory

The thunder clouds are developed at heights 1 to 2 km above the ground level and may extend up to 12 to 14 km above the ground.

For thunder clouds and charge formation air currents, moisture and specific temperature range are required.

The air currents controlled by the temperature gradient move upwards carrying moisture and water droplets.

The temperature is 0°C at about 4 km from the ground and may reach -50°C at about 12 km height.

But water droplets do not freeze as soon as the temperature is 0°C. They freeze below -40°C only as solid particles on which crystalline ice patterns develop and grow.

The larger the number of solid sites or nuclei present, the higher is the temperature ($> -40^{\circ}\text{C}$) at which the ice crystals grow.

Thus in clouds, the effective freezing temperature range is around -33°C to -40°C . The water droplets in the thunder cloud are blown up by air currents and get super cooled over a range of heights and temperatures.

When such freezing occurs, the crystals grow into large masses and due to their weight and gravitational force start moving downwards. Thus, a thunder cloud consists of super cooled water droplets moving upwards and large hail stones moving downwards.

When the upward moving super cooled water droplets act on cooler hail stone, it freezes partially, i.e. the outer layer of the water droplets freezes forming a shell with water inside. When the process of cooling extends to inside warmer water in the core, it expands, thereby splintering and spraying the frozen ice shell.

The splinters being fine in size are moved up by the air currents and carry a net positive charge to the upper region of the cloud.

The hail stones that travel downwards carry an equivalent negative charge to the lower regions of the cloud and thus negative charge builds up in the bottom side of the cloud.

Mason's theory

According to Mason, the ice splinters should carry only positive charge upwards. Water being ionic in nature has concentration of H^+ and OH^- ions. The ion density depends on the temperature. Thus, in an ice slab with upper and lower surfaces at temperatures T_1 and T_2 , ($T_1 < T_2$), there will be a higher concentration of ions in the lower region.

However, since H^+ ions are much lighter, they diffuse much faster all over the volume. Therefore, the lower portion which is warmer will have a net negative charge density, and hence the upper portion, i.e. cooler region will have a net positive charge density.

The outer shells of the freezed water droplets coming into contact with hail stones will be relatively cooler (than their inner core—warmer water) and therefore acquire a net positive charge.

When the shell splinters, the charge carried by them in the upward direction is positive.

MECHANISM OF LIGHTNING

4. Give the mathematical model of lightning discharges and explain them. (Apr' 22)

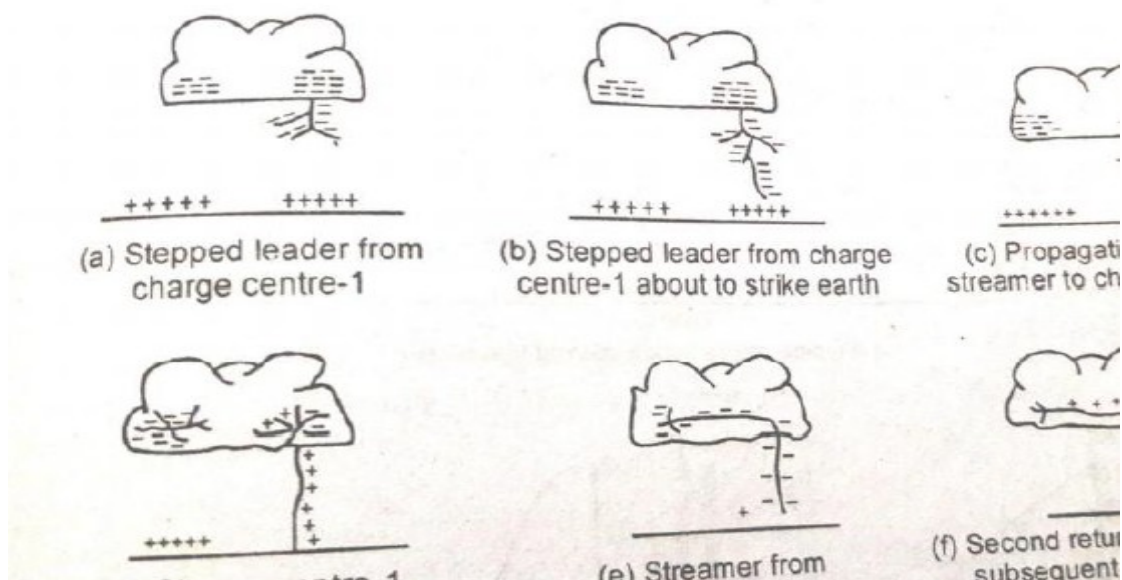
(or)

What are the mechanisms by which lighting strokes develop and induce over voltages on overhead power lines? (Dec'12)

When the electric field intensity at some point in the charge concentrated cloud exceeds the breakdown value of the moist ionized air (~ 10 kV/cm), an electric streamer with plasma starts towards the ground with a velocity of about 1/10 times that of the light, but may progress only about 50 m or so before it comes to a halt emitting a bright flash of light. The halt may be due to insufficient build-up of electric charge at its head and not sufficient to maintain the necessary field gradient for further progress of the streamer. But after a short interval of about 100 μs , the streamer again starts out repeating its performance. The total time required for such a stepped leader to reach the ground may be 20 ms. The path may be quite lustruous,

depending on the local conditions in air as well as the electric field gradients. Branches from the initial leader may also be formed. Since the progress of this leader stroke is by a series of jumps, it is referred as stepped leader. The lightning consists of few separate discharges starting from a leader discharge and culminates in return strokes or main discharges. The velocity of the leader stroke of the first discharge may be 1.5×10^7 cm/s, of the succeeding leader strokes about 10^8 cm/s, and of the return strokes may be 1.5×10^9 to 1.5×10^{10} cm/s (about 0.05 to 0.5 times the velocity of light). After the leader touches the ground, the return stroke follows. As the leader moves towards the ground, positive charge is directly accumulated under the head of the stroke or canal. By the time the stroke reaches the ground or comes sufficiently near the ground, the electrical field intensity on the ground side is sufficiently large to build up the path. Hence, the positive charge returns to the cloud neutralizing the negative charge, and hence a heavy current flows through the path. The velocity of the return or main stroke ranges from 0.05 to 0.5 times the velocity of light, and currents will be of the order of 1000 to 250,000 A. The return strokes vanish before they reached the cloud, suggesting that the charge involved is that conferred to the stroke itself.

The duration of the main or return stroke is about $100\mu\text{s}$ or more. The diameters of the return strokes were estimated to be about 1 to 2cm but the corona envelop may be approximately 50 cm. The return strokes also may develop branches but the charges in the branches are neutralized in succession so that their further progress is arrested. This stroke is called continuous leader, and return stroke for this leader follows with much less current. The interval between the repeated strokes may be from 0.6 ms to 500 ms with an average of 30ms. Multiple strokes may last for 1s. The total duration of the lightning may be more than 1s. The current from the ground by the main return stroke may have a peak value of 250,000A.



Mathematical Model for Lightning

During the charge formation process, the cloud may be considered to be a nonconductor. Hence, various potentials may be assumed at different parts of the cloud. If the charging process is continued, it is probable

that the gradient at certain parts of the charged region exceeds the breakdown strength of the air or moist air in the cloud. Hence, local breakdown takes place within the cloud.

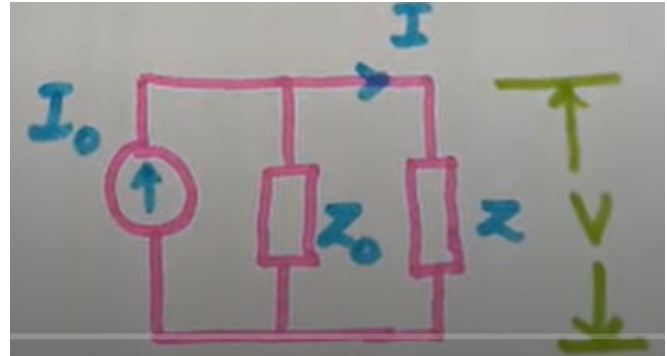
This local discharge may finally lead to a situation wherein a large reservoir of charges involving a considerable mass of cloud hangs over the ground, with the air between the cloud and the ground as a dielectric.

When a streamer discharge occurs to ground by first a leader stroke, followed by main strokes with considerable currents flowing, the lightning stroke may be thought to be a current source of value I_0 with source impedance Z_0 discharging to earth. If the stroke strikes an object of impedance Z , the voltage built across it may be taken as

$$V = IZ$$

$$= I_0 * \frac{Z_0}{Z_0 + Z} * Z$$

$$= I_0 * \frac{Z}{1 + \frac{Z}{Z_0}}$$



The source impedance of the lightning channels are not known exactly, but it is estimated to be about 1000 to 3000 Ω .

Transmission line have surge impedances less than 500 Ω

Surge impedance of Overhead lines 300 to 500 Ω

Surge impedance of Ground wires 100 to 150 Ω

Surge impedance of Towers 10 to 50 Ω

Therefore, the value Z/Z_0 will usually be less than 0.1 and hence can be neglected. Hence, the voltage rise of lines, etc. may be taken to be approximately $V = I_0 Z$, where I_0 is the lightning stroke current and Z the line surge impedance.

The incidence of lightning strikes on transmission lines and sub-stations is related to the degree of thunderstorm activity.

It is based on the level of 'Thunderstorm days' (TD).

Thunderstorm Days (or) Isokeraunic Level:

It is defined as the number of days in a year when thunder is heard or recorded in a particular location.

If a measure of ground flashover density (N_g) is obtained, then the number of ground flashovers can be computed from the TD level.

$$N_g = (0.1 \text{ to } 0.2) \text{ TD/strokes/km}^2\text{-year.}$$

A value of 30 to 50 may be taken for the coastal areas and for the central parts of India.

Switching Surges and Temporary Overvoltages

5. Give the origin and characteristics of switching surges and explain the causes of over voltage due to switching surges in EHV and UHV system. (Dec'11)

(or)

Explain the control measures for over voltage due to switching surge. (Dec'19)

(or)

What are the methods used to control of over voltages due to switching? Explain briefly

(or)

Explain the characteristics of switching surges with typical wave shapes clearly. (Apr' 22)

(or)

What are the causes for switching and power frequency over voltages? How are they controlled in power systems? (Dec'13)

If the transmission voltages were about 220 kV and below, overvoltages due to lightning were of very high order and overvoltages generated inside the system were not of much consequence. With increase in transmission voltages, (400 kV and above) the overvoltages generated inside the system reached the same order of magnitude as those of lightning overvoltages, or higher. Secondly, the overvoltages thus generated last for longer durations and therefore are severe and more dangerous to the system. Unlike the lightning overvoltages, the switching and other types of overvoltages depend on the normal voltage of the system and hence increase with increased system voltage.

In the EHV range, it is the switching surge and other types of overvoltages that determine the insulation level of the lines and other equipment and consequently, they also determine their dimensions and costs.

Origin of Switching Surges:

- ❖ Making and breaking of electric circuits with switchgear.
- ❖ In circuit breaking operation, switching surges with a high rate of rise of voltage may cause repeated restriking of the arc between the contacts of a circuit breaker.
- ❖ High natural frequencies of the system.
- ❖ Damped normal frequency voltage component.
- ❖ Restriking and recovery voltage of the system with successive reflected waves from terminations.

Characteristics of Switching Surges:

The wave shapes of switching surges are quite different and may have origin from any of the following sources.

- ✓ De-energizing of transmission lines, cables, shunt capacitor, banks, etc.
- ✓ Disconnection of unloaded transformers, reactors, etc.
- ✓ Energization or reclosing of lines and reactive loads.
- ✓ Sudden switching off of loads.
- ✓ Short circuits and fault clearances.

- ✓ Resonance phenomenon like Ferro-resonance, arcing grounds, etc.

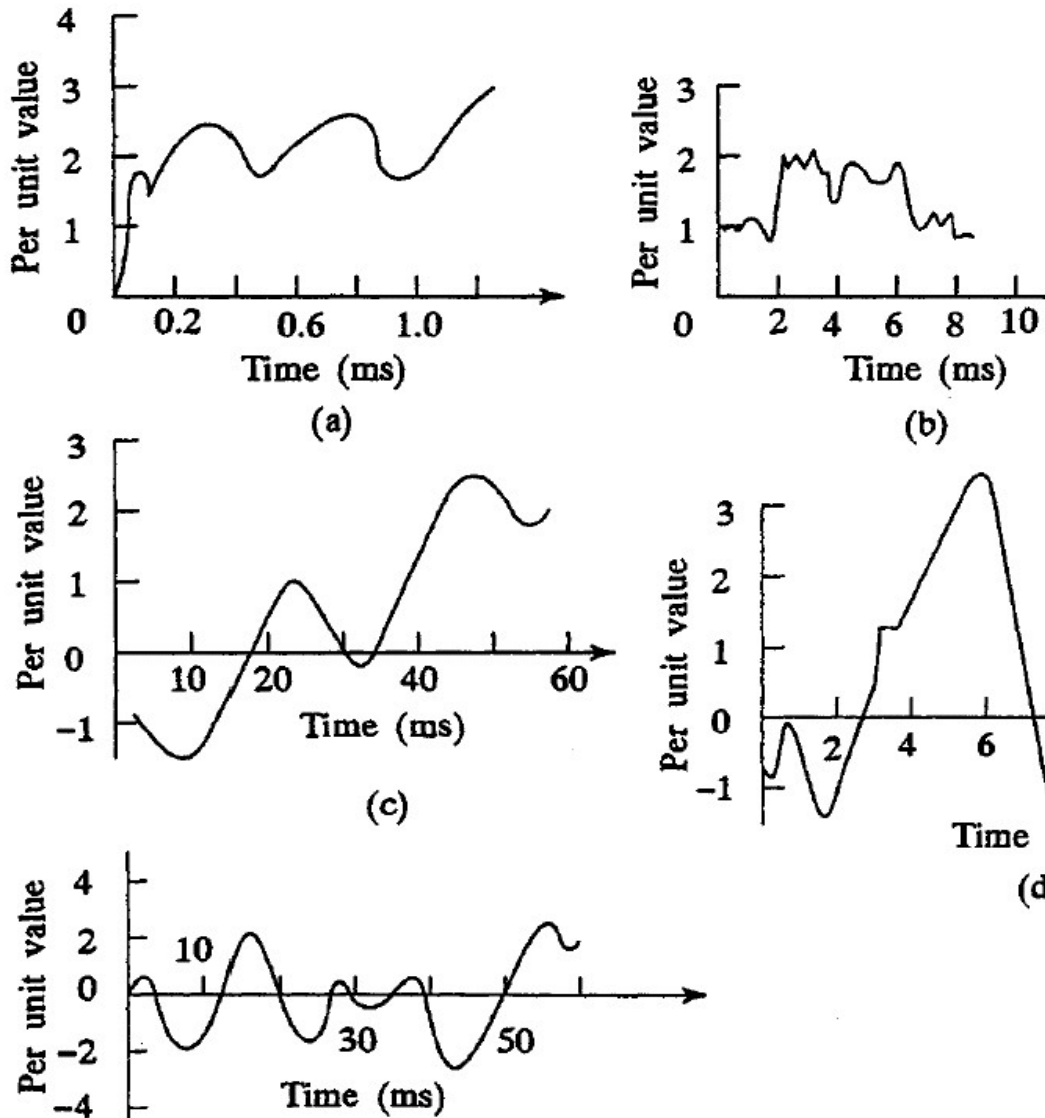


Fig. Typical waveshapes of switching surge voltages

Switching Overvoltages in EHV and UHV Systems:

Overvoltages are generated in EHV systems when there is a sudden release of internal energy stored either in the electrostatic form (in the capacitance) or in the electromagnetic form (in the inductance).

This may happen due to

- ❖ Interruption of low inductive currents (current chopping) by high speed circuit breakers. This occurs when the transformers or reactors are switched off.
- ❖ Interruption of small capacitive currents, such as switching off of unloaded lines etc.

- ❖ Ferro-resonance condition. This may occur when poles of a circuit breaker do not close simultaneously.
- ❖ Energization of long EHV or UHV lines.
- ❖ Single pole closing of circuit breaker.
- ❖ Interruption of fault current when the L-G or L-L fault is cleared.
- ❖ Resistance switching used in circuit breakers.
- ❖ Switching lines terminated by transformers.
- ❖ Series capacitor compensated lines.
- ❖ Sparking of the surge diverter located at the receiving end of the line to limit the lightning overvoltages.

The measures taken to control or reduce the overvoltages are

- (i) One step or multi-step energisation of lines by preinsertion of resistors,
- (ii) Phase controlled closing of circuit breakers with proper sensors,
- (iii) Drainage of trapped charges on long lines before the reclosing of the lines,
- (iv) Limiting the overvoltages by using surge diverters.

Power Frequency Overvoltages in Power Systems:

The main causes for power frequency and its harmonic overvoltages are

- (a) Sudden loss of loads,
- (b) Disconnection of inductive loads or connection of capacitive loads,
- (c) Ferranti effect, unsymmetrical faults, and
- (d) Saturation in transformers, etc.

(a) Sudden Load Rejection

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

(b) Ferranti Effect

Long uncompensated transmission lines exhibit voltage rise at the receiving end.

(c) Ground Faults and Their Effects

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

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

$$\frac{R_0}{X_1} \leq 1.0$$

Where R_0 - Zero sequence resistance

X_0 - Zero sequence reactance

X_1 - Positive sequence reactance of the system

The rise in voltage of the healthy phases does not usually exceed 1.4 per unit.

(d) Saturation Effects

When voltages above the rated value are applied to transformers, their magnetizing currents (no load currents also) increase rapidly and may be about the full rated current for 50% overvoltage. These magnetizing currents are not sinusoidal in nature but are of a peaky waveform. The third, fifth, and seventh harmonic contents may present. For higher harmonics a series resonance between the transformer inductance and the line capacitance can occur which may produce even higher voltages.

Reflection and Refraction of Travelling waves

6. Discuss the step by step procedure for constructing Bewley's Lattice diagram with an example.

(May'14).

(or)

Define surge impedance of a line. Obtain the expression of reflection and transmission of travelling waves at transition points. (Dec'14)

To understand the travelling wave phenomenon over transmission line consider Fig. (a). 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 in Fig. (b) by a large number of L and C sections.

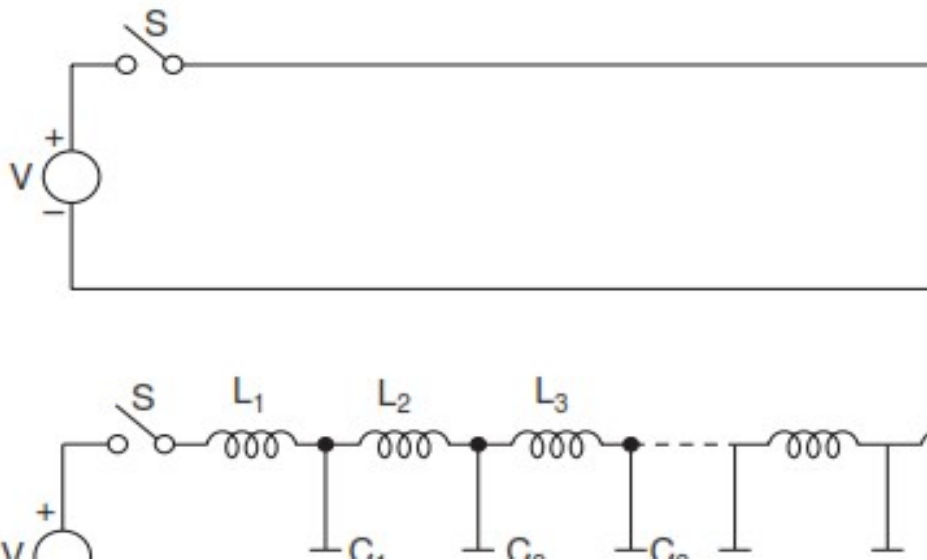


Fig. (a) Long transmission line, (b) Equivalent section of a long transmission line

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 upto a distance x is given by the line.

$$q = VCx \quad (1)$$

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

$$I = \frac{dq}{dt} = vC \frac{dx}{dt} \quad (2)$$

Here dx/dt is the velocity of the travelling wave over the line conductor and let this be represented by v .

Then

$$I = VCv \quad (3)$$

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

$$V = ILx \quad (4)$$

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

$$V = IL \frac{dx}{dt} = ILv \quad (5)$$

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

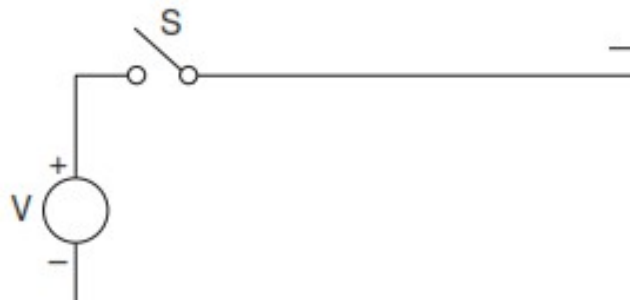
$$\frac{V}{I} = \frac{ILv}{VCv} = \frac{IL}{VC} \quad \frac{V^2}{I^2} = \frac{L}{C}$$

$$\frac{V}{I} = \sqrt{\frac{L}{C}} \quad (6)$$

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

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 ; then

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

$$\text{(or)} \quad \left(\frac{e}{I}\right)^2 = \frac{L}{C}$$

$$\text{or} \quad e = IZ = V$$

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

$$\text{Refracted wave} = \text{Incident wave} + \text{Reflected wave}$$

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

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.

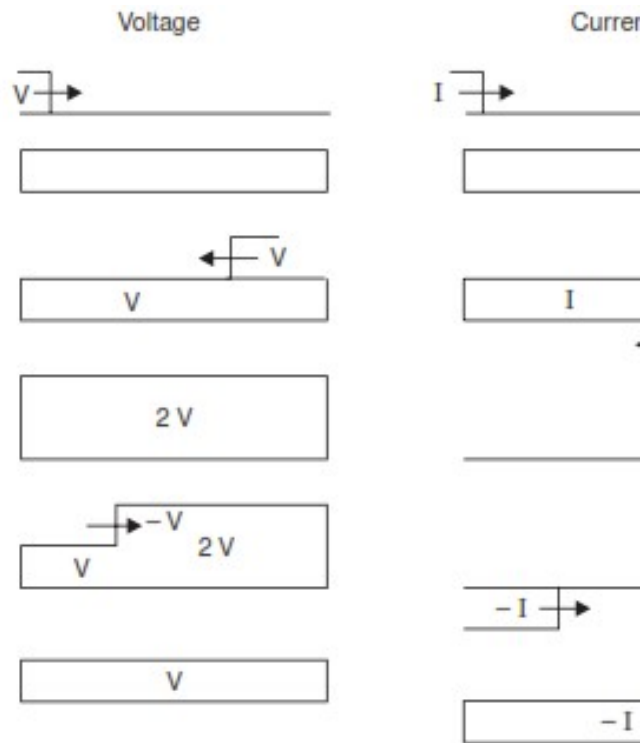


Fig. Variation of voltage and current in an open-ended line

After the voltage and current waves are reflected back from the open end, they reach the source end, 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

$$\frac{1}{2}Ldx i^2 = \frac{1}{2}Cdx V^2$$

$$\text{or } iZ = V$$

$$\text{or } i = \frac{V}{Z} = I$$

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 $(I + I) = 2I$ amperes. 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.

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 $V/Z = I$. 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.

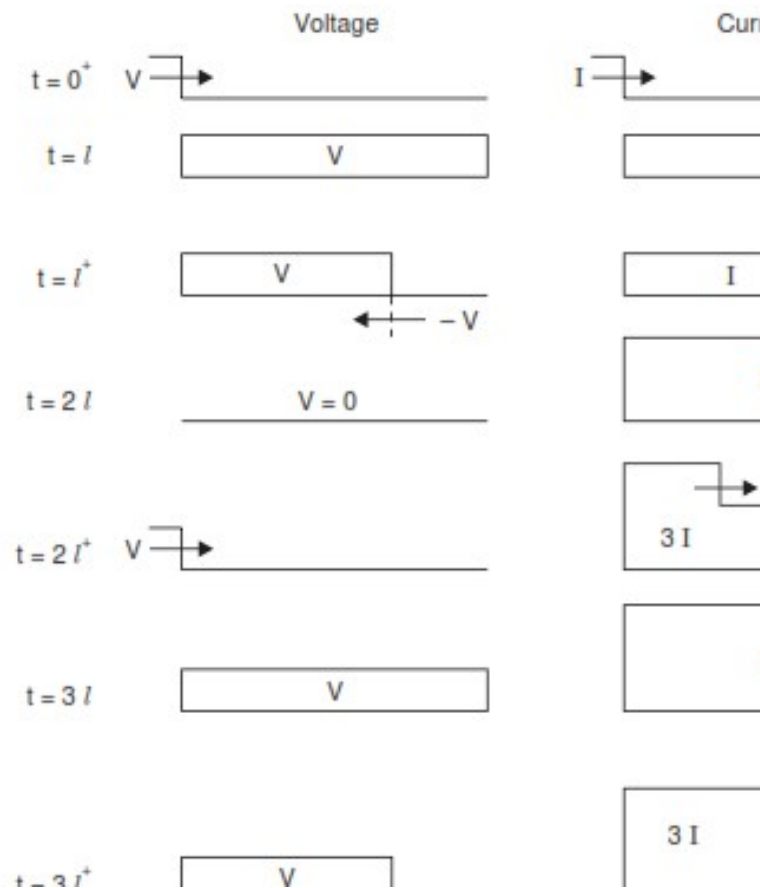


Fig. Variation of voltage and current in a short ended line

Line Terminated Through a Resistance

Let Z be the surge impedance of the line terminated through a resistance R (Fig.). 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

$$\frac{V''}{R} = \frac{V}{Z} - \frac{V'}{Z} = \frac{V}{Z} - \frac{V'' - V}{Z} = \frac{2V}{Z} -$$

$$\text{or} \quad V'' = \frac{2VR}{Z + R}$$

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

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

or

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

and

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

From the relations above, the coefficient of reflection for current

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

and for voltage waves

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

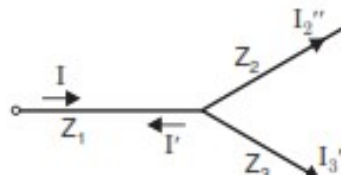
Similarly, the coefficient of reflection for current waves

$$R - Z$$

Reflection and Refraction at a T-junction

A voltage wave V is travelling over the line with surge impedance Z 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.



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

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

$$I_2'' = \frac{V''}{Z_2} \quad \text{and} \quad I_3'' = \frac{V''}{Z_3}$$

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

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

$$V'' = \frac{2V/Z_1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3}}$$

Protection of Transmission Lines against Overvoltages

7. Discuss about the various control techniques for switching and power frequency over voltages
(May'11), (May'14)

(or)

Elaborate the discussion on protection of power system equipments using protective devices.
(Dec'11)

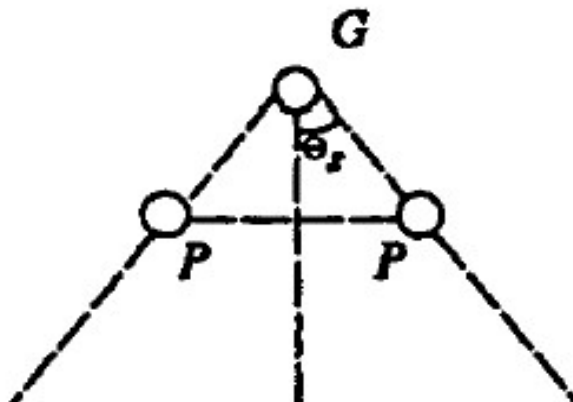
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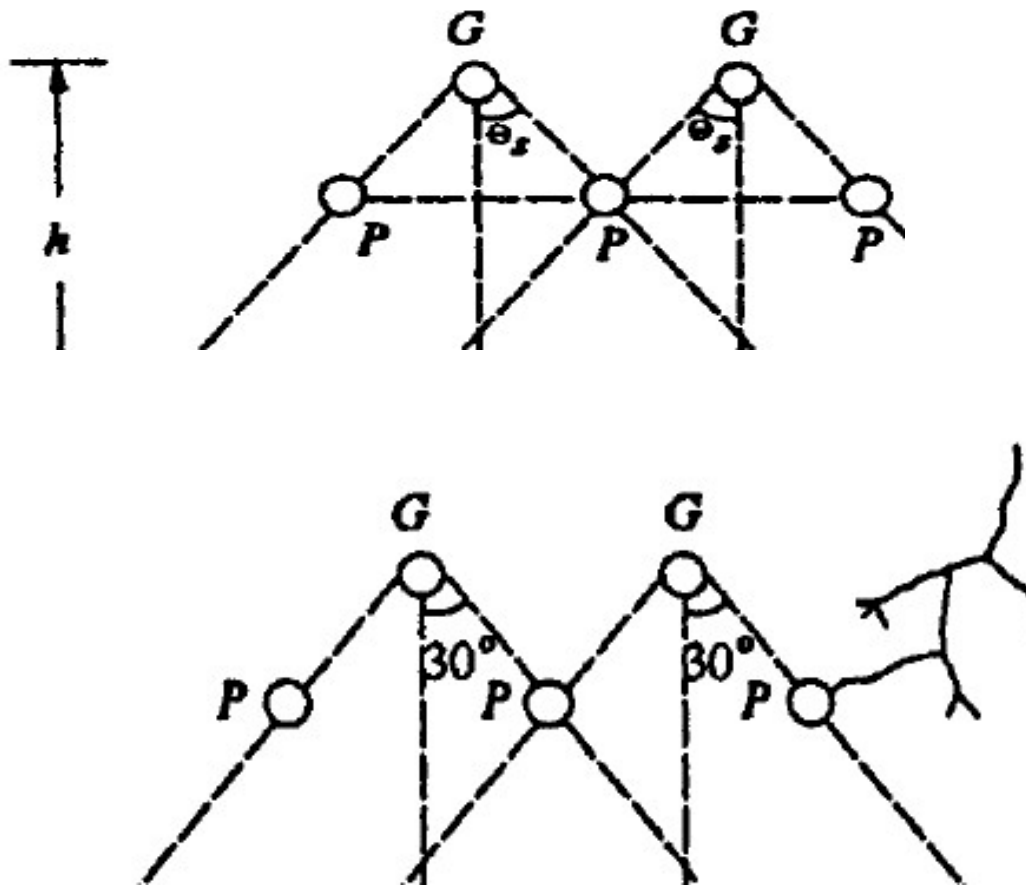
What are the causes for power frequency over voltage? How they are controlled in power systems?
(Dec'19), (Dec'12)

Protection of transmission lines against natural or lightning overvoltages and minimizing the lightning overvoltages are done by suitable line designs, providing guard and ground wires, and using surge diverters.

(a) Lightning Protection Using Shielded Wires or Ground Wires

Ground wire is a conductor run parallel to the main conductor of the transmission line supported on the same tower and earthed at every equally and regularly spaced towers. It is run above the main conductor of the line. The ground wire shields the transmission line conductor from induced charges, from clouds as well as from a lightning discharge.





G — Ground wire
 h — Height of the ground wire from the earth surface
 P-P — Phase wires from the earth surface
 θ_s — Shielding angle

Fig. Shielding arrangement of overhead lines by ground wires

b) Protection Using Ground Rods and Counter-Poise Wires

When a line is shielded, the lightning strikes either the tower or the ground wire. The path for drainage of the charge and lightning current is (a) through the tower frame to ground, (b) through the ground line in opposite directions from the point of striking. Thus the ground wire reduces the instantaneous potential to which the tower top rises considerably.

Ground rods are a number of rods about 15mm diameter and 2.5 to 3 m long driven into the ground. In hard soils the rods may be much longer and can be driven to a depth of, say, 50 m. They are usually made of galvanized iron or copper bearing steel. The spacing of the rods, the number of rods, and the depth to which they are driven depend on the desired tower footing resistance. With 10 rods of 4 m long and spaced 5 m apart, connected to the legs of the tower, the dynamic or effective resistance may be reduced to 10Ω .

The above effect is alternatively achieved by using counter-poise wires. Counterpoise

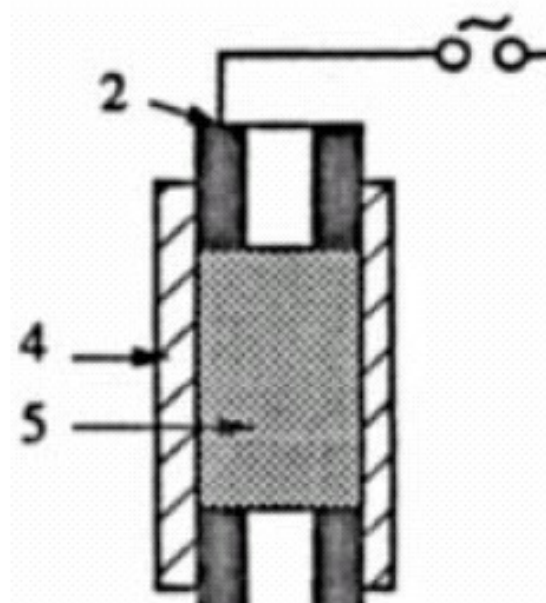
wires are buried in the ground at a depth of 0.5 to 1.0 m, running parallel to the transmission line conductors and connected to the tower legs. These wires may be 50 to 100 m long. These are found to be more effective than driven rods and the surge impedance of the tower may be reduced to as low as 25Ω .

(c) Protective Devices

In regions where lightning strokes are intensive or heavy, the overhead lines within these zones are fitted with shunt protected devices. On the line itself two devices known as expulsion gaps and protector tubes are used.

(i) Expulsion gaps

Expulsion gap is a device which consists of a spark gap together with an arc quenching device which extinguishes the current arc when the gaps breakover due to overvoltages. A typical such arrangement is shown in Fig. This essentially consists of a rod gap in air in series with a second gap enclosed within a fibre tube. In the event of an overvoltage, both the spark gaps breakdown simultaneously. The current due to the overvoltage is limited only by the tower footing resistance and the surge impedance of the ground wires. The internal arc in the fibre tube due to lightning current vapourizes a small portion of the fibre material. The gas thus produced, being a mixture of water vapour and the decomposed fibre product, drive away the arc products and ionized air. When the follow-on power frequency current passes through zero value, the arc is extinguished and the path becomes open circuited. Meanwhile the insulation recovers its dielectric strength, and the normal conditions are established.



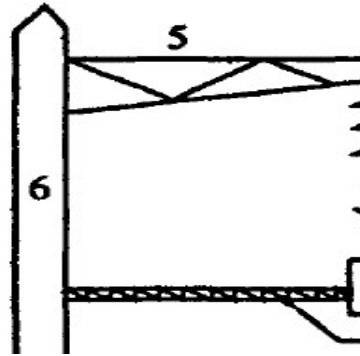
1. External series gap 2. Upper electrode 3. Ground electrode 4. Fibre tube 5. Hollow space

Fig. Expulsion gap

(ii) Protector tubes

A protector tube is similar to the expulsion gap in, construction and principle. It also consists of a rod or spark gap in air formed by the line conductor and its high voltage terminal. It is mounted underneath the

line conductor on a tower. The arrangement is shown in Fig. The hollow gap in the expulsion tube is replaced by a nonlinear element which offers very high impedance at low currents but has low impedance for high or lightning currents. When an overvoltage occurs and the spark gap breaks down, the current is limited both by its own resistance and the tower footing resistance. The overvoltage on the line is reduced to the voltage drop across the protector tube. After the surge current is diverted and discharged to the ground, the follow-on normal power frequency current will be limited by its high resistance. After the current zero of power frequency, the spark gap recovers the insulation strength quickly.



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

Fig. Protector tube mounting

(iii) Rod gaps

A much simpler and effective protective device is a rod-gap. However, it does not meet the complete requirement. The sparkover voltage of a rod gap depends on the atmospheric conditions.

(iv) Surge diverters or lightning arresters

Surge diverters or lightning arresters are devices used at sub-stations and at line terminations to discharge the lightning overvoltages and short duration switching surges. These are usually mounted at the line end at the nearest point to the sub-station. They have a flashover voltage power than that of any other insulation or apparatus at the sub-station.

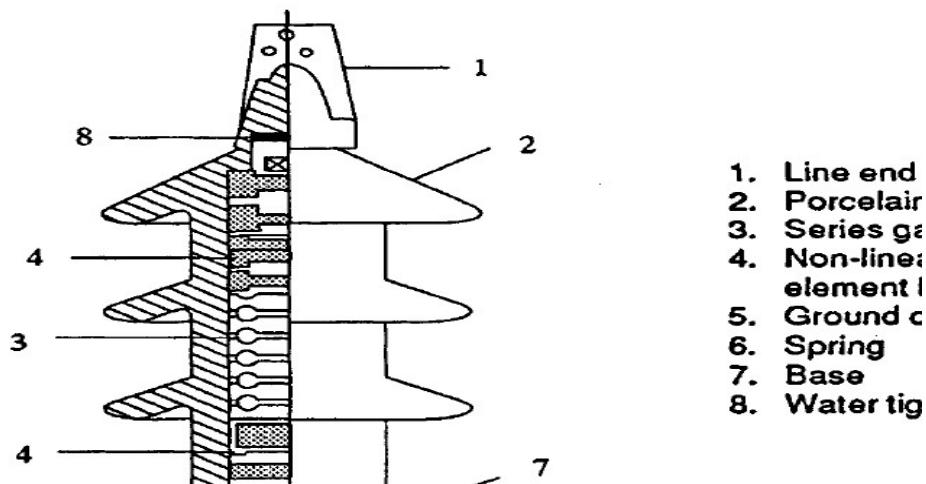


Fig. Non-linear element surge diverter

UNIT II - DIELECTRICAL BREAKDOWN

Gaseous breakdown:

1. Describe about the primary and secondary ionization processes.

(Dec'18)

(or)

Discuss the various ionization processes.

Ionization Processes

A gas in its normal state is almost a perfect insulator. However, when a high voltage is applied between the two electrodes immersed in a gaseous medium, the gas becomes a conductor and an electrical breakdown occurs.

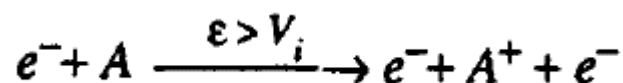
The processes that are primarily responsible for the breakdown of a gas are **ionization by collision, photo-ionization, and the secondary ionization processes.**

Ionization by Collision

The process of liberating an electron from a gas molecule with the simultaneous production of a positive ion is called ionisation.

In the process of ionisation by collision, a free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion. In a low pressure gas column in which an electric field E is applied across two plane parallel electrodes, as shown in Fig. then, any electron starting at the cathode will be accelerated more and more between collisions with other gas molecules during its travel towards the anode.

If the energy (ϵ) gained during this travel between collisions exceeds the ionisation potential, V_i , which is the energy required to dislodge an electron from its atomic shell, then ionisation takes place. This process can be represented as



Where, A is the atom, A^{+} is the positive ion and e^{-} is the electron.

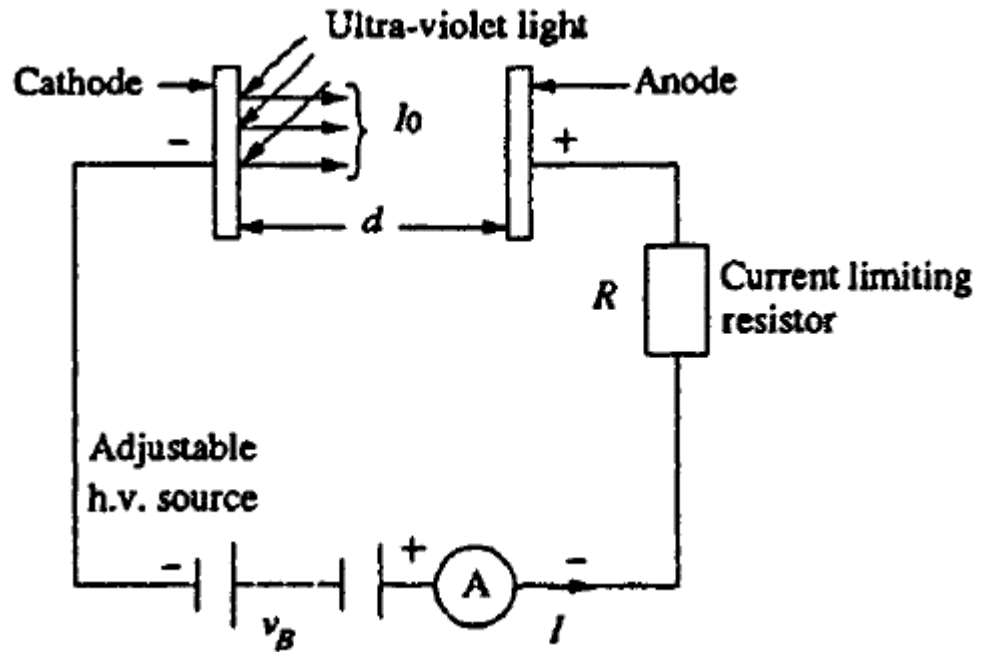


Fig. Arrangement for study of a Townsend discharge

Photo-ionization

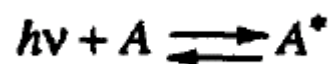
Photo-ionisation occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionisation potential.

There are several processes by which radiation can be absorbed by atoms or molecules. They are

- (a) excitation of the atom to a higher energy state
- (b) continuous absorption by direct excitation of the atom or dissociation of diatomic molecule or direct ionisation etc.

Just as an excited atom emits radiation when the electron returns to the lower state or to the ground state, the reverse process takes place when an atom absorbs radiation.

This reversible process can be expressed as



Ionisation occurs when

$$\lambda \leq c \cdot \frac{h}{V_i}$$

where, h is the Planck's constant, c is the velocity of light, λ is the wavelength of the incident radiation and V_i is the ionisation energy of the atom.

Secondary Ionisation Processes

Secondary ionisation processes by which secondary electrons are produced are the one which sustain a discharge after it is established due to ionisation by collision and photo-ionization.

a) Electron Emission due to Positive Ion Impact

Positive ions are formed due to ionisation by collision or by photo-ionisation, and being positively charged, they travel towards the cathode. A positive ion approaching a metallic cathode can cause emission of electrons from the cathode by giving up its kinetic energy on impact. If the total energy of the positive ion, namely, the sum of its kinetic energy and the ionisation energy, is greater than twice the work function of the metal, then one electron will be ejected and a second electron will neutralise the ion.

(b) Electron Emission due to Photons

To cause an electron to escape from a metal, it should be given enough energy to overcome the surface potential barrier. The energy can also be supplied in the form of a photon of ultraviolet light of suitable frequency.

c) Electron Emission due to Metastable and Neutral Atoms

A metastable atom or molecule is an excited particle whose lifetime is very large (10^{-3} s) compared to the lifetime of an ordinary particle (10^{-8} s). Electrons can be ejected from the metal surface by the impact of excited (metastable) atoms, provided that their total energy is sufficient to overcome the work function. This process is most easily observed with metastable atoms, because the lifetime of other excited states is too short for them to reach the cathode and cause electron emission, unless they originate very near to the cathode surface.

2. Deduce the Townsend's break down criteria. Also define the Townsend's primary and secondary ionization coefficients.

(Dec'19)

(or)

Explain about Townsend's current growth equation (Townsend's first ionization Process)

Assume that n_0 electrons are emitted from the cathode. When one electron collides with a neutral particle, a positive ion and an electron are formed. This is called an ionizing collision. Let α be the average number of ionizing collisions made by an electron per centimetre travel

in the direction of the field (α depends on gas pressure p and E/p , and is called the **Townsend's first ionization coefficient**). At any distance x from the cathode, let the number of electrons be n_x . When these n_x electrons travel a further distance of dx they give rise to $(\alpha n_x dx)$ electrons.

At $x = 0, n_x = n_0$

Also, $\frac{dn_x}{dx} = \alpha n_x$; or $n_x = n_0 \exp(\alpha x)$

Then, the number of electrons reaching the anode ($x = d$) will be

$$n_d = n_0 \exp(\alpha d)$$

The number of new electrons created, on the average, by each electron is

$$\exp(\alpha d) - 1 = \frac{n_d - n_0}{n_0}$$

Therefore, the average current in the gap, which is equal to the number of electrons travelling per second will be

$$I = I_0 \exp(\alpha d)$$

where I_0 is the initial current at the cathode.

Current Growth in the Presence of Secondary Processes (Townsend's Secondary Ionization Process)

The single avalanche process described in the previous section becomes complete when the initial set of electrons reaches the anode. However, since the amplification of electrons $[\exp(\alpha d)]$ is occurring in the field, the probability of additional new electrons being liberated in the gap by other mechanisms increases, and these new electrons create further avalanches. The other mechanisms are

- (i) The positive ions liberated may have sufficient energy to cause liberation of electrons from the cathode when they impinge on it.
- (ii) The excited atoms or molecules in avalanches may emit photons, and this will lead to the emission of electrons due to photo-emission.
- (iii) The metastable particles may diffuse back causing electron emission.

The electrons produced by these processes are called secondary electrons. The secondary ionization coefficient γ is defined in the same way as α , as the net number of secondary electrons produced per incident positive ion, photon, excited particle, or metastable particle, and the total value of γ is the sum of the individual coefficients due to the three different

processes, i.e., $\gamma = \gamma_1 + \gamma_2 + \gamma_3$. γ is called the **Townsend's secondary ionization coefficient** and is a function of the gas pressure p and E/p .

Assume

n_0' = number of secondary electrons produced due to secondary (γ) processes.

n_0'' = total number of electrons leaving the cathode.

Then $n_0'' = n_0 + n_0'$

The total number of electrons n reaching the anode becomes,

$$n = n_0'' \exp(\alpha d) = (n_0 + n_0') \exp(\alpha d);$$

and

$$n_0' = \gamma [n - (n_0 + n_0')]$$

Eliminating n_0' ,

$$n = \frac{n_0 \exp(\alpha d)}{1 - \gamma [\exp(\alpha d) - 1]}$$

or

$$I = \frac{I_0 \exp(\alpha d)}{1 - \gamma [\exp(\alpha d) - 1]}$$

..... (a)

Narrate about Townsend's criterion for breakdown

(or)

Explain the Townsends criterion for a spark.

(May'11)

Equation (a) gives the total average current in a gap before the occurrence of breakdown. As the distance between the electrodes d is increased, the denominator of the equation tends to zero, and at some critical distance $d = ds$.

$$1 - \gamma [\exp(\alpha d) - 1] = 0$$

For values of $d < ds$, I is approximately equal to I_0 , and if the external source for the supply of I_0 is removed, I becomes zero. If $d = ds$, $I \rightarrow \infty$ and the current will be limited only by the resistance of the power supply and the external circuit. This condition is called Townsend's breakdown criterion and can be written as

$$\gamma [\exp(\alpha d) - 1] = 1$$

Normally, $\exp(\alpha d)$ is very large, and hence the above equation reduces to

$$\gamma \exp(\alpha d) = 1$$

For a given gap spacing and at a give pressure the value of the voltage V which gives the values of α and γ satisfying the breakdown criterion is called the spark breakdown voltage V_s and the corresponding distance ds is called the sparking distance.

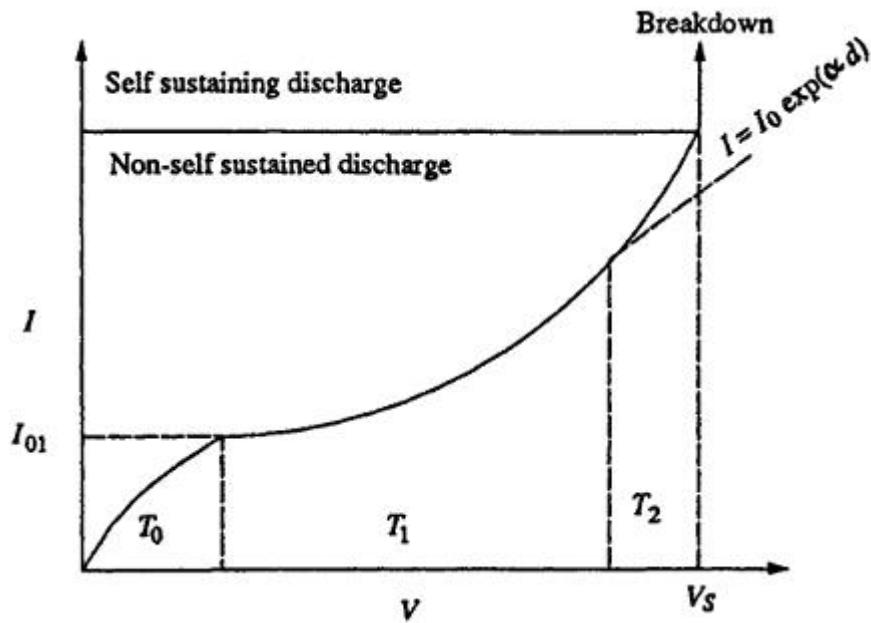


Fig. Typical current growth curve in a townsend discharge

Time Lags for Breakdown

There is a time difference between the application of a voltage sufficient to cause breakdown and the occurrence of breakdown itself. This time difference is called the time lag.

The Townsend criterion for breakdown is satisfied, only if at least one electron is present in the gap between the electrodes. In the case of applied d.c. or slowly varying (50 Hz a.c) voltages, there is no difficulty in satisfying this condition. However, with rapidly varying voltages of short duration ($\approx 10^{-6}$ s), the initiatory electron may not be present in the gap, and in the absence of such an electron breakdown cannot occur. The time t which lapses between the application of the voltage sufficient to cause breakdown and the appearance of the initiating electron is called a statistical time lag (t_s) of the gap. The appearance of electrons is usually statistically distributed. After the appearance of the electron, a time t_t is required for the

ionization processes to develop fully to cause the breakdown of the gap, and this time is called the formative time lag (t_f). The total time $t_s + t_f = t$ is called the total time lag.

Gaseous breakdown in uniform fields (Streamer Theory of Breakdown in Gases)

3. Discuss the streamer theory of breakdown in gases. (May'14)

(or)

Explain about gaseous breakdown in uniform fields

Townsend mechanism when applied to breakdown at atmospheric pressure was found to have certain drawbacks. Firstly, according to the Townsend theory, current growth occurs as a result of ionization processes only. But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap. Secondly, the mechanism predicts time lags of the order of 10^{-5} S, while in actual practice breakdown was observed to occur at very short times of the order of 10^{-8} S. Also, while the Townsend mechanism predicts a very diffused form of discharge, in actual practice, discharges were found to be filamentary and irregular.

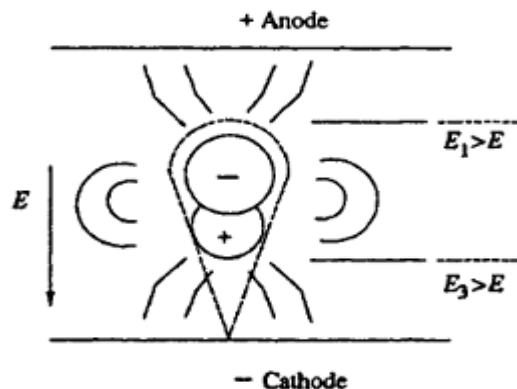


Fig. Effect of space charge produced by an avalanche on the applied electric field

The Streamer theory predicts the development of a spark discharge directly from a single avalanche in which the space charge developed by the avalanche itself is said to transform the avalanche into a plasma streamer. Consider Fig. A single electron starting at the cathode by ionization builds up an avalanche that crosses the gap. The electrons in the avalanche move very fast compared with the positive ions. By the time the electrons reach the anode the positive ions are virtually in their original positions and form a positive space charge

at the anode. This enhances the field, and the secondary avalanches are formed from the few electrons produced due to photo-ionization in the space charge region.

This occurs first near the anode where the space charge is maximum. This results in a further increase in the space charge. This process is very fast and the positive space charge extends to the cathode very rapidly resulting in the formation of a streamer. Comparatively narrow luminous tracks occurring at breakdown at high pressures are called streamers.

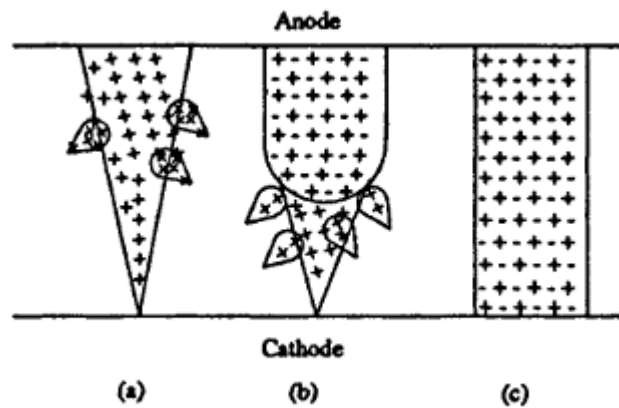


Fig. Cathode directed streamer

As soon as the streamer tip approaches the cathode, a cathode spot is formed and a stream of electrons rush from the cathode to neutralize the positive space charge in the streamer; the result is a spark, and the spark breakdown has occurred. The three successive stages in the development of the streamer are shown diagrammatically in Fig. 2.13 in which (a) shows the stage when avalanche has crossed the gap, (b) shows that the streamer has crossed half the gap length, and (c) shows that the gap has been bridged by a conducting channel.

PASCHEN'S LAW

The breakdown criterion in gases is given as

$$\gamma[\exp(\alpha d) - 1] = 1$$

where the coefficients α and γ are functions of E/p , i.e

$$\begin{aligned} \frac{\alpha}{p} &= f_1\left(\frac{E}{p}\right) \\ \text{and} \quad \gamma &= f_2\left(\frac{E}{p}\right) \\ \text{Also} \quad E &= \frac{V}{d} \end{aligned}$$

Substituting for E in the expressions for α and γ

$$f_2\left(\frac{V}{pd}\right)\left[\exp\left\{pd f_1\left(\frac{V}{pd}\right)\right\} - 1\right] = 1$$

This equation shows a relationship between V and pd , and implies that the breakdown voltage varies as the product pd varies.

$$V = f(pd)$$

This equation is known as Paschen's law.

Gaseous breakdown in non-uniform fields

4. Explain in detail the breakdown mechanism in non-uniform fields and phenomenon of Corona. (Dec'11)

In non-uniform fields, such as coaxial cylinders, point-plane and sphere-plane gaps, the applied field varies across the gap. Similarly, Townsend's first ionization coefficient (α) also varies with the gap. Hence αd in Townsend's criterion is rewritten by replacing αd by $\int_0^d \alpha dx$.

Townsend's criterion for breakdown becomes

$$\gamma \left\{ \exp\left[\int_0^d \alpha dx\right] - 1 \right\} = 1$$

Meek and Raether also discussed the non-uniform field breakdown process as applied to their Streamer theory, and the Meek's equation for the radial field at the head of an avalanche when it has crossed a distance x is modified as

$$E_r = \frac{5.27 \times 10^{-7} \alpha_x \exp\left(\int_0^x \alpha dx\right)}{(x/p)^{1/2}} \text{ V/cm}$$

where α_x is the value of α at the head of the avalanche, and p is the gas pressure. The criterion for the formation of the streamer is reached when the space charge field E_r approaches a value equal to the applied field at the head of the avalanche.

This equation has been successfully used for determining the corona onset voltages of many non-uniform geometries.

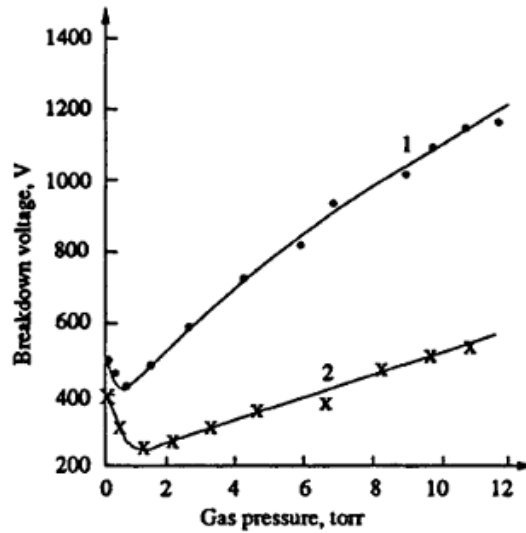


Fig. Breakdown characteristics for nitrogen between a wire and a coaxial cylinder of radii 0.083 and 2.3 cm. 1-wire positive, 2-wire negative

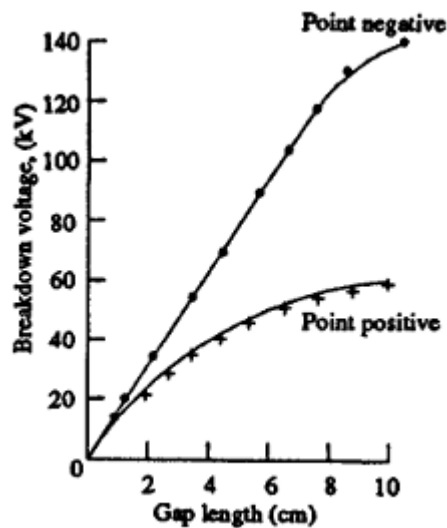


Fig. d.c. breakdown characteristics for air between 30° conical point and a plane
Corona Discharges

5. What is corona discharge? Explain clearly anode and cathode coronas. (Dec'13)
(or)

List out the problems caused by corona discharge. (Dec'12)

If the field is non-uniform, an increase in voltage will first cause a discharge in the gas to appear at points with highest electric field intensity, namely at sharp points or where the electrodes are curved or on transmission lines. This form of discharge is called a corona

discharge and can be observed as a bluish luminiscence. This phenomenon is always accompanied by a hissing noise, and the air surrounding the corona region becomes converted into ozone. Corona is responsible for considerable loss of power from high voltage transmission lines, and it leads to the deterioration of insulation due to the combined action of the bombardment of ions and of the chemical compounds formed during discharges. Corona also gives rise to radio interference.

The voltage gradient required to produce visual a.c. corona in air at a conductor surface, called the **corona inception field**, can be approximately given for the case of parallel wires of radius r as

$$E_v = 30md \left[1 + \frac{0.301}{\sqrt{dr}} \right]$$

For the case of coaxial cylinders, whose inner cylinder has a radius r the equation becomes

$$E_c = 31md \left[1 + \frac{0.308}{\sqrt{dr}} \right]$$

where m is the surface irregularity factor which becomes equal to unity for highly polished smooth wires; d is the relative air density correction factor given by,

$$d = \frac{0.392b}{(273 + t)}$$

where b is the atmospheric pressure in torr, and t is the temperature in $^{\circ}\text{C}$, $d = 1$ at 760 torr and 25°C . The expressions were found to hold good from atmospheric pressure down to a pressure of several torr.

When the voltage is positive, corona appears as a uniform bluish white sheath over the entire surface of the conductor. On the other hand, when the voltage is negative, the corona will appear like reddish glowing spots distributed along the length of the wire. Point-plane gaps in air showed that when point is negative, corona appears as current pulses called **Trichel pulses**, and the repetition frequency of these pulses increases as the applied voltage is increased and decreases with decrease in pressure. On the other hand, observations when the point is positive in air showed that the corona current increases steadily with voltage. At sufficiently high voltage, current amplification increases rapidly with voltage, up to a current of about 10^{-7}A ,

after which the current becomes pulsed with repetition frequency of about 1 kHz composed of small bursts. This form of corona is called **burst corona**.

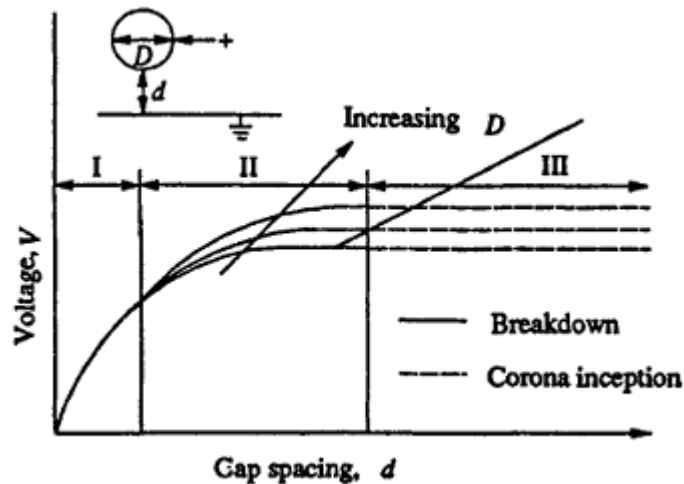


Fig. Breakdown and corona inception characteristics for spheres of different diameters in sphere-plane gap geometry

The corona inception and breakdown voltages of the sphere-plane arrangement are shown in Fig. From this figure it can be seen that

- (a) at small spacings (region I), the field is uniform, and the breakdown voltage mainly depends on the spacing;
- (b) at fairly large spacings (region II), the field is non-uniform, and the breakdown voltage depends both on the sphere diameter and the spacing; and
- (c) at large spacings (region III), the field is non-uniform, and the breakdown is preceded by corona and is controlled only by the spacing. The corona inception voltage mainly depends on the sphere diameter.

Vacuum breakdown

6. Explain clearly various processes of electric breakdown in vacuum. (May'11), (May'19), (Dec'13), (May'14)

Vacuum

A vacuum system which is used to create vacuum is a system in which the pressure is maintained at a value much below the atmospheric pressure. In vacuum systems the pressure is always measured in terms of millimetres of mercury, where one standard atmosphere is equal

to 760 millimetres of mercury at a temperature of 0°C . The term "millimetres of mercury" has been standardised as "Torr", where one millimetre of mercury is taken as equal to one Torr.

Vacuum b.d. can be broadly divided into three categories

- (a) Particle exchange mechanism
- (b) Field emission mechanism
- (c) Clump theory

(a) Particle Exchange Mechanism

In this mechanism it is assumed that a charged particle would be emitted from one electrode under the action of the high electric field, and when it impinges on the other electrode, it liberates oppositely charged particles. These particles are accelerated by the applied voltage back to the first electrode where they release more of the original type of particles. When this process becomes cumulative, a chain reaction occurs which leads to the breakdown of the gap.

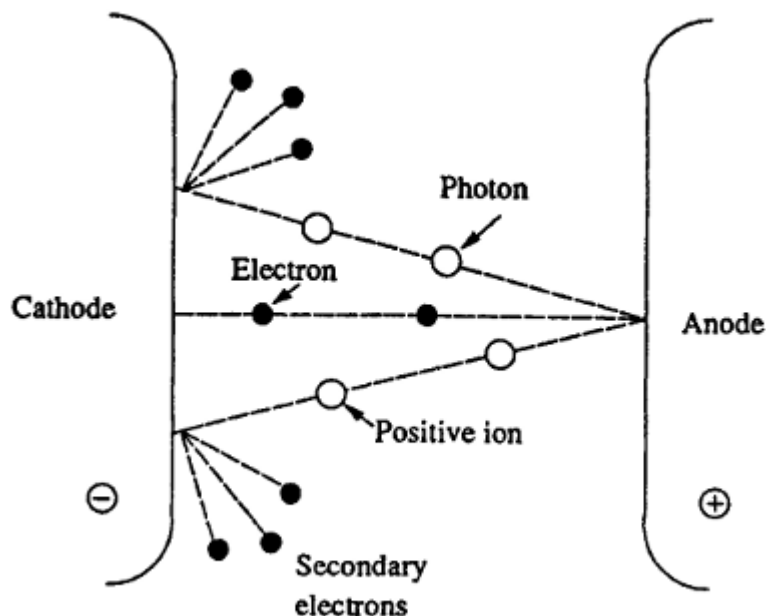


Fig. Particle exchange mechanism of vacuum breakdown

The particle-exchange mechanism involves electrons, positive ions, photons and the absorbed gases at the electrode surfaces. Qualitatively, an electron present in the vacuum gap is accelerated towards the anode, and on impact releases A positive ions and C photons. These positive ions are accelerated towards the cathode, and on impact each positive ion liberates B electrons and each photon liberates D electrons. This is shown schematically in Fig.. The

breakdown will occur if the coefficients of production of secondary electrons exceeds unity. Mathematically, the condition for breakdown can be written as

$$(AB + CD) > 1$$

Later, Trump and Van de Graaff measured these coefficients and showed that they were too small for this process to take place. Accordingly, this theory was modified to allow for the presence of negative ions and the criterion for breakdown then becomes

$$(AB + EF) > 1$$

Where A and B are the same as before and E and F represent the coefficients for negative and positive ion liberation by positive and negative ions.

(b) Field Emission Theory

(i) Anode Heating Mechanism

This theory postulates that electrons produced at small micro-projections on the cathode due to field emission bombard the anode causing a local rise in temperature and release gases and vapours into the vacuum gap. These electrons ionise the atoms of the gas and produce positive ions. These positive ions arrive at the cathode, increase the primary electron emission due to space charge formation and produce secondary electrons by bombarding the surface. The process continues until a sufficient number of electrons are produced to give rise to breakdown, as in the case of a low pressure Townsend type gas discharge.

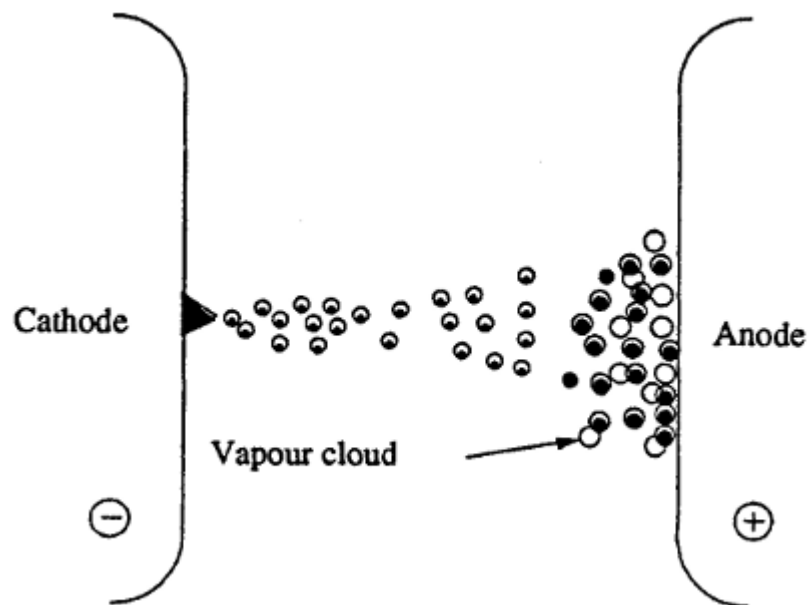


Fig. Electron beam anode heating mechanism of vacuum breakdown

(ii) Cathode Heating Mechanism

This mechanism postulates that near the breakdown voltages of the gap, sharp points on the cathode surface are responsible for the existence of the pre-breakdown current, which is generated according to the field emission process described below. This current causes resistive heating at the tip of a point and when a critical current density is reached, the tip melts and explodes, thus initiating vacuum discharge. This mechanism is called field emission.. Thus, the initiation of breakdown depends on the conditions and the properties of the cathode surface.

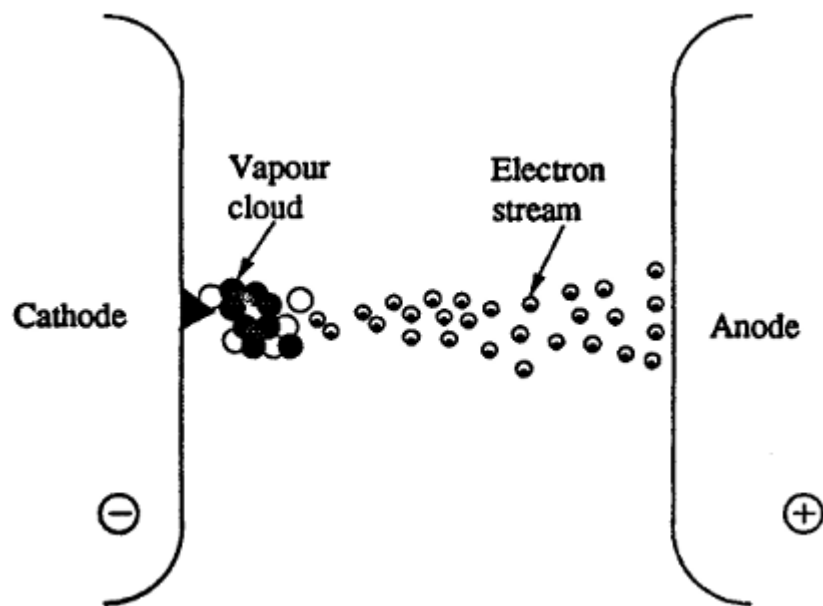


Fig. Breakdown in vacuum caused by the heating of a microprojection on the cathode

(c) Clump Mechanism

Basically this theory has been developed on the following assumptions:

- (i) A loosely bound particle (clump) exists on one of the electrode surfaces.
- (ii) On the application of a high voltage, this particle gets charged, subsequently gets detached from the mother electrode, and is accelerated across the gap.
- (iii) The breakdown occurs due to a discharge in the vapour or gas released by the impact of the particle at the target electrode.

Cranberg was the first to propose this theory. He initially assumed that breakdown will occur when the energy per unit area, W , delivered to the target electrode by a clump exceeds a value C , a constant, characteristic of a given pair of electrodes. The quantity W is the product of gap voltage (V) and the charge density on the clump. The latter is proportional to the electric field E at the electrode of origin. The criterion for breakdown, therefore, is

$$VE = C'$$

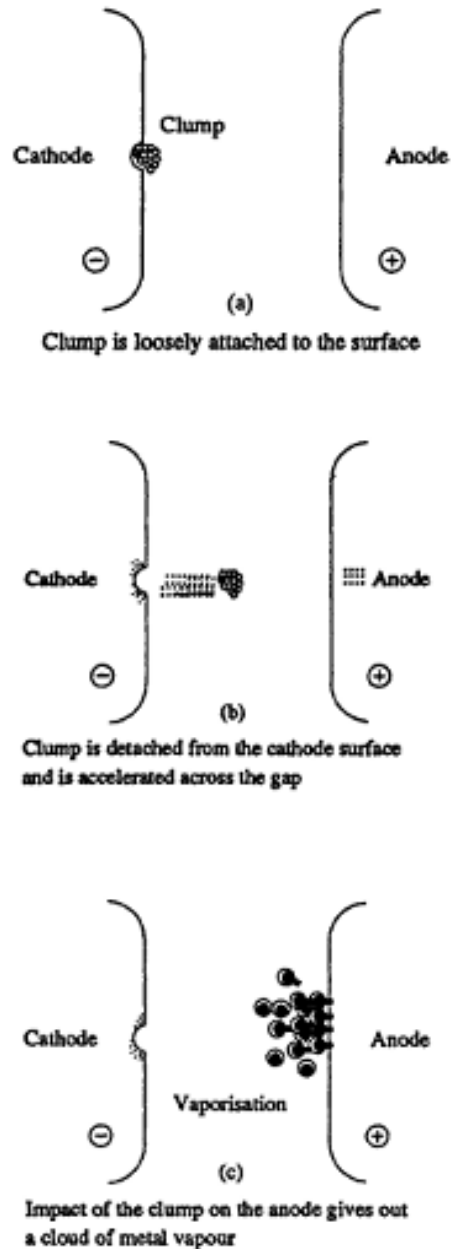


Fig. (a, b, c) Clump mechanism of vacuum breakdown

In case of parallel plane electrodes the field $E = V/d$ where d is the distance between the electrodes. So the generalised criterion for breakdown becomes

$$V = (Cd)^{1/2}$$

where C is another constant involving C' and the electrode surface conditions.

Conduction and breakdown in pure liquids

7. Discuss the characteristics of liquid dielectrics.

(Dec'12)

When low electric fields less than 1 kV/cm are applied, conductivities of 10^{-18} to 10^{-20} mho/cm are obtained. These are probably due to the impurities remaining after purification.

However, when the fields are high ($> 100 \text{ kV/cm}$) the currents not only increase rapidly, but also undergo violent fluctuations which will die down after some time.

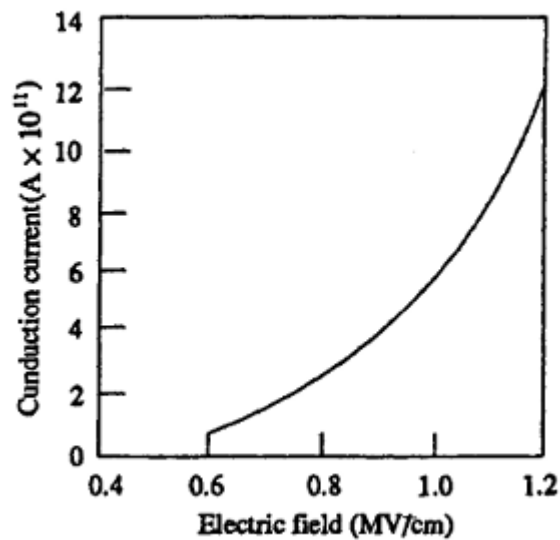


Fig- Conduction current-electric field characteristic in hexane at high fields

This is the condition nearer to breakdown. However, if this figure is redrawn starting from very small currents, a current-electric field characteristic as shown in Fig. can be obtained. This curve will have three distinct regions as shown. At very low fields the current is due to the dissociation of ions. With intermediate fields the current reaches a saturation value, and at high fields the current generated because of the field-aided electron emission from the cathode gets multiplied in the liquid medium by a Townsend type of mechanism. The current multiplication also occurs from the electrons generated at the interfaces of liquid and impurities. The increase in current by these processes continues till breakdown occurs.

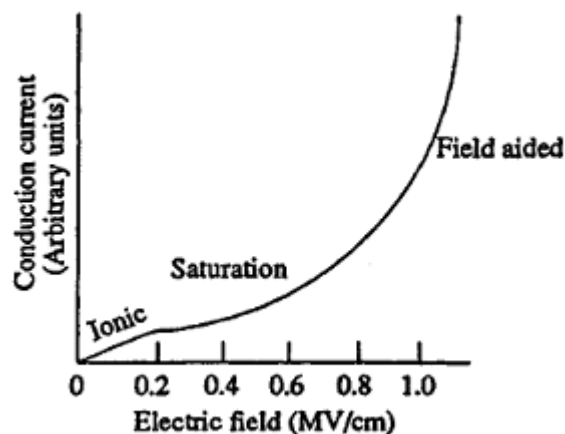


Fig. Conduction current-electric field characteristic in a hydrocarbon liquid

The exact mechanism of current growth is not known; however, it appears that the electrons are generated from the cathode by field emission of electrons. The electrons so liberated get multiplied by a process similar to Townsend's primary and secondary ionization in gases. As the breakdown field is approached, the current increases rapidly due to a process similar to the primary ionization process and also the positive ions reaching the cathode generate secondary electrons, leading to breakdown. The breakdown voltage depends on the field, gap separation, cathode work-function, and the temperature of the cathode.

Conduction and Breakdown in Commercial Liquids

8. Explain briefly various theories of breakdown in liquid dielectrics. (May'11)

(or)

Explain the various theories of breakdown mechanism of the commercial liquid dielectrics. (May'19) (Dec'13), (Dec'14)

Commercial insulating liquids are not chemically pure and have impurities like gas bubbles, suspended particles, etc. These impurities reduce the breakdown strength of these liquids considerably. The breakdown mechanisms are also considerably influenced by the presence of these impurities. In addition, when breakdown occurs in these liquids, additional gases and gas bubbles are evolved and solid decomposition products are formed. The electrode surfaces become rough, and at times explosive sounds are heard due to the generation of impulsive pressure through the liquid.

The breakdown mechanism in commercial liquids is dependent, as seen above, on several factors, such as, the nature and condition of the electrodes, the physical properties of the liquid, and the impurities and gases present in the liquid. Several theories have been proposed to explain the breakdown in liquids, and they are classified as follows:

- (a) Suspended Particle Mechanism
- (b) Cavitation and Bubble Mechanism
- (c) Stressed Oil Volume Mechanism

Suspended Particle Theory

In commercial liquids, the presence of solid impurities cannot be avoided. These impurities will be present as fibres or as dispersed solid particles. The permittivity of these

particles (ϵ_2) will be different from the permittivity of the liquid (ϵ_1). If we consider these impurities to be spherical particles of radius r , and if the applied field is E , then the particles experience a force F , where

$$F = \frac{1}{2r^3} \frac{(\epsilon_2 - \epsilon_1)}{2\epsilon_1 + \epsilon_2} \text{grad } E^2$$

This force is directed towards areas of maximum stress, if $\epsilon_2 > \epsilon_1$ for example, in the case of the presence of solid particles like paper in the liquid. On the other hand, if only gas bubbles are present in the liquid, i.e. $\epsilon_2 < \epsilon_1$, the force will be in the direction of areas of lower stress. If the voltage is continuously applied (d.c.) or the duration of the voltage is long (a.c.), then this force drives the particles towards the areas of maximum stress. If the number of particles present are large, they become aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes.

If there is only a single conducting particle between the electrodes, it will give rise to local field enhancement depending on its shape. If this field exceeds the breakdown strength of the liquid, local breakdown will occur near the particle, and this will result in the formation of gas bubbles which may lead to the breakdown of the liquid.

Cavitation and the Bubble Theory

In many liquids, the breakdown strength depends strongly on the applied hydrostatic pressure, suggesting that a change of phase of the medium is involved in the breakdown process, which in other words means that a kind of vapour bubble formed is responsible for breakdown. The following processes have been suggested to be responsible for the formation of the vapour bubbles:

- (a) Gas pockets at the surfaces of the electrodes;
- (b) electrostatic repulsive forces between space charges which may be sufficient to overcome the surface tension;
- (c) gaseous products due to the dissociation of liquid molecules by electron collisions; and
- (d) vapourization of the liquid by corona type discharge from sharp points and irregularities on the electrode surfaces.

Once a bubble is formed it will elongate in the direction of the electric field under the influence of electrostatic forces. The volume of the bubble remains constant during elongation. Breakdown occurs when the voltage drop along the length of the bubble becomes equal to the

minimum value on the Paschen's curve for the gas in the bubble. The breakdown field is given as

$$E_0 = \frac{1}{(\epsilon_1 - \epsilon_2)} \left[\frac{2\pi\sigma(2\epsilon_1 + \epsilon_2)}{r} \left\{ \frac{\pi}{4} \sqrt{\left(\frac{V_b}{2rE_0} \right)} - 1 \right\} \right]^{\frac{1}{2}}$$

where σ is the surface tension of the liquid, ϵ_1 is the permittivity of the liquid, ϵ_2 is the permittivity of the gas bubble, r is the initial radius of the bubble assumed as a sphere and V_b is the voltage drop in the bubble (corresponding to minimum on the Paschen's curve). From this equation, it can be seen that the breakdown strength depends on the initial size of the bubble which in turn is influenced by the hydrostatic pressure and temperature of the liquid.

Thermal Mechanism of Breakdown

High current pulses are believed to originate from the tips of the microscopic projections on the cathode surface. These high density current pulses give rise to localised heating of the oil which may lead to the formation of vapour bubbles. The vapour bubbles are formed when the energy exceeds 10 W/cm . When a bubble is formed, breakdown follows, either because of its elongation to a critical size or when it completely bridges the gap between the electrodes. In either case, it will result in the formation of a spark. According to this mechanism, the breakdown strength depends on the pressure and the molecular structure of the liquid.

Stressed Oil Volume Theory

In commercial liquids where minute traces of impurities are present, the breakdown strength is determined by the "largest possible impurity" or "weak link". The electrical breakdown strength of the oil is defined by the weakest region in the oil, namely, the region which is stressed to the maximum and by the volume of oil included in that region. In non-uniform fields, the stressed oil volume is taken as the volume which is contained between the maximum stress ($E_{\max}$) contour and 0.9 $E_{\max}$ contour. According to this theory the breakdown strength is inversely proportional to the stressed oil volume.

The breakdown voltage is highly influenced by the gas content in the oil, the viscosity of the oil, and the presence of other impurities. These being uniformly distributed, increase in the stressed oil volume consequently results in a reduction in the breakdown voltage.

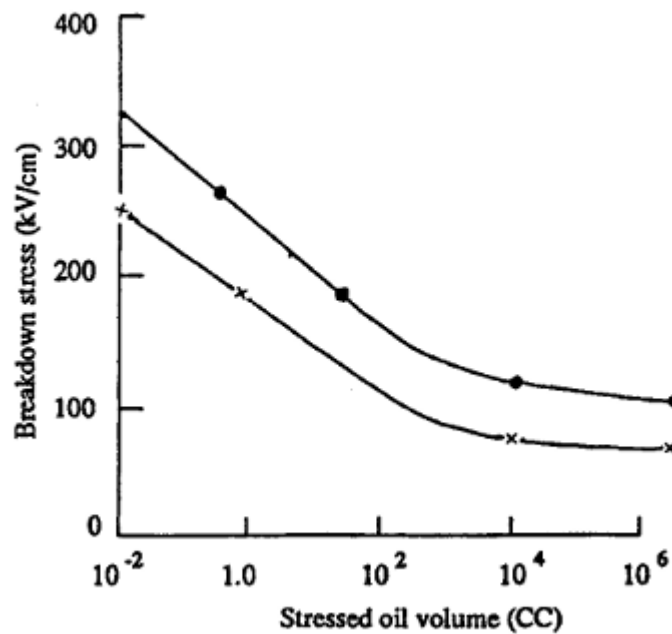


Fig. Power frequency (50 Hz) a.c. breakdown stress as a function of the stressed oil volume

Maintenance of oil quality

Even though new synthetic materials with better mechanical and thermal properties are being developed, the use of oil/paper complex for high voltages is still finding applications. Oil, besides being a good insulating medium, it allows better dispersion of heat. It allows transfer and absorption of water, air and residues created by the ageing of the solid insulation. In order to achieve operational requirements, it must be treated to attain high degree of purity. Whatever be the nature of impurities whether solid, liquid or gaseous, these bring down the dielectric strength of oil materially. Oil at 20°C with water contents of 44 ppm will have 25% of its normal dielectric strength. The presence of water in paper not only increases the loss angle $\tan \delta$, it accelerates the process of ageing. Similarly, air dissolved in oil produces a risk of forming bubble and reduces the dielectric strength of oil.

Air Absorption: The process of air absorption can be compared to a diffusing phenomenon in which a gaseous substance in this case air is in contact with liquid (oil here).

Filtration and Treatment Under Vacuum: Different types of filters have been used. Filter press with soft and hard filter papers is found to be more suitable for insulating oil. Due to hygroscopic properties of the paper, oil is predried before filtering. Therefore, this oil can not

be used for high voltage insulation. The subsequent process of drying is carried out in a specially, designed tank under vacuum. The oil is distributed over a large surface by a so-called “Rasching-ring” degassing column. Through this process, both the complete drying and degassing are achieved simultaneously. By suitable selection of the various components of the plant *e.g.*, rate of flow of oil, degassing surface, vacuum pump etc., a desired degree of purity can be obtained.

Centrifugal Method: This method is helpful in partially extracting solid impurities and free water. It is totally ineffective as far as removal of water and dissolved gases is concerned and oil treated in this manner is even over-saturated with air as air, is thoroughly mixed into it during the process. However, if the centrifugal device is kept in a tank kept under vacuum, partial improvement can be obtained. But the slight increase in efficiency of oil achieved is out of proportion to the additional costs involved.

Adsorption Columns: Here the oil is made to flow through one or several columns filled with an adsorbing agent either in the form of grains or powder. Following adsorbing agents have been used:

- (i) Fuller earth
- (ii) Silica gel
- (iii) Molecular sieves

Activated Fuller earths absorb carbonyl and hydroxyl groups which from the principal ageing products of oil and small amount of humidity. Best results of oil treatment are obtained by a combination of Fuller earth and subsequent drying under vacuum.

Electrostatic Filters: The oil to be treated is passed between the two electrodes placed in a container. The electrostatic field charges the impurities and traces of water which are then attracted and retained by the foam coated electrodes. This method of drying oil is found to be economical if the water content of the oil is less than 2 ppm. It is, therefore, essential that the oil is dried before hand if the water content is large. Also, it is desirable that the oil flow should be slow if efficient filtering is required. Therefore, for industrial application where large quantity of oil is to be filtered, large number of filters will have to be connected in parallel which may prove uneconomical.

Breakdown mechanisms in solid dielectrics

9. Classify the various breakdown mechanisms occurring on solid dielectrics and explain them briefly.

(Dec'13) (Dec'19)

Solid dielectric materials are used in all kinds of electrical circuits and devices to insulate one current carrying part from another when they operate at different voltages. A good dielectric should have low dielectric loss, high mechanical strength, should be free from gaseous inclusions, and moisture, and be resistant to thermal and chemical deterioration. Solid

dielectrics have higher breakdown strength compared to liquids and gases. When breakdown occurs, solids get permanently damaged while gases fully and liquids partly recover their dielectric strength after the applied electric field is removed.

The mechanism of breakdown is a complex phenomena in the case of solids, and varies depending on the time of application of voltage as shown in Fig. The various breakdown mechanisms can be classified as follows:

- (a) intrinsic or ionic breakdown,
- (b) electromechanical breakdown,
- (c) failure due to treeing and tracking,
- (d) thermal breakdown,
- (e) electrochemical breakdown, and
- (f) breakdown due to internal discharges.

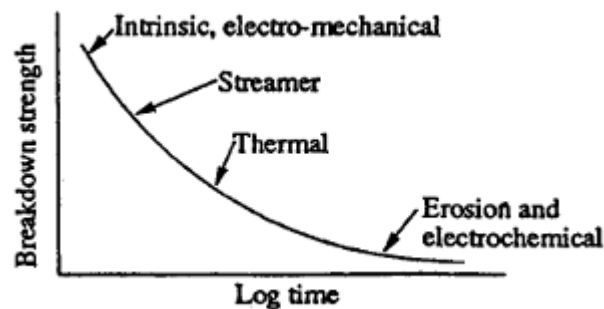


Fig. Variation of breakdown strength with time after application of voltage

a) Intrinsic Breakdown

When voltages are applied only for short durations of the order of 10^{-8} s the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength. This highest dielectric strength can be obtained only under the best experimental conditions when all extraneous influences have been isolated and the value depends only on the structure of the material and the temperature.

Intrinsic breakdown depends upon the presence of free electrons which are capable of migration through the lattice of the dielectric. Usually, a small number of conduction electrons are present in solid dielectrics, along with some structural imperfections and small amounts of impurities. The impurity atoms, or molecules or both act as traps for the conduction electrons up to certain ranges of electric fields and temperatures. When these ranges are exceeded, additional electrons in addition to trapped electrons are released, and these electrons participate

in the conduction process. Based on this principle, two types of intrinsic breakdown mechanisms have been proposed.

Electronic Breakdown

Intrinsic breakdown occurs in time of the order of 10^{-8} s and therefore is assumed to be electronic in nature. The initial density of conduction (free) electrons is also assumed to be large, and electron-electron collisions occur. When an electric field is applied, electrons gain energy from the electric field and cross the forbidden energy gap from the valency to the conduction band. When this process is repeated, more and more electrons become available in the conduction band, eventually leading to breakdown.

Avalanche or Streamer Breakdown

This is similar to breakdown in gases due to cumulative ionization. Conduction electrons gain sufficient energy above a certain critical electric field and cause liberation of electrons from the lattice atoms by collisions. Under uniform field conditions, if the electrodes are embedded in the specimen, breakdown will occur when an electron avalanche bridges the electrode gap.

An electron within the dielectric, starting from the cathode will drift towards the anode and during this motion gains energy from the field and loses it during collisions. When the energy gained by an electron exceeds the lattice ionization potential, an additional electron will be liberated due to collision of the first electron. This process repeats itself resulting in the formation of an electron avalanche. Breakdown will occur, when the avalanche exceeds a certain critical size.

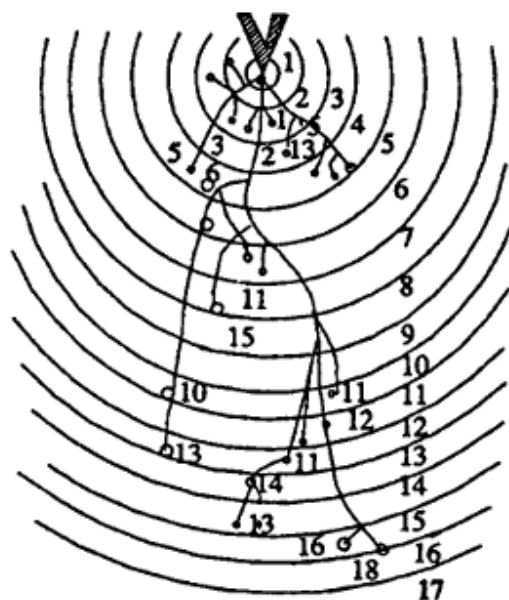


Fig. Breakdown channels in perspex between point-plane electrodes

b) Electromechanical Breakdown

When solid dielectrics are subjected to high electric fields, failure occurs due to electrostatic compressive forces which can exceed the mechanical compressive strength. If the thickness of the specimen is d_0 and is compressed to a thickness d under an applied voltage V , then the electrically developed compressive stress is in equilibrium, if

$$\epsilon_0 \epsilon_r \frac{V^2}{2d^2} = Y \ln \left[\frac{d_0}{d} \right]$$

where Y is the Young's modulus.

c) Thermal Breakdown

The breakdown voltage of a solid dielectric should increase with its thickness. But this is true only up to a certain thickness above which the heat generated in the dielectric due to the flow of current determines the conduction.

When an electric field is applied to a dielectric, conduction current, however small it may be, flows through the material. The current heats up the specimen and the temperature rises. The heat generated is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces. Equilibrium is reached when the heat used to raise the temperature of the dielectric, plus the heat radiated out, equals the heat generated. The heat generated under d.c. stress E is given as

$$W_{d.c.} = E^2 \sigma \quad \text{W/cm}^3$$

where, σ is the d.c. conductivity of the specimen.

Under a.c. fields, the heat generated

$$W_{a.c.} = \frac{E^2 f \epsilon_r \tan \delta}{1.8 \times 10^{12}} \quad \text{W/cm}^3$$

where, f = frequency in Hz,
 δ = loss angle of the dielectric material, and
 E = rms value.

The heat dissipated (W_T) is given by

$$W_T = C_V \frac{dT}{dt} + \text{div} (K \text{ grad } T)$$

where, C_V = specific heat of the specimen,
 T = temperature of the specimen,
 K = thermal conductivity of the specimen, and
 t = time over which the heat is dissipated.

Equilibrium is reached when the heat generated ($W_{d.c.}$ or $W_{a.c.}$) becomes equal to the heat dissipated (W_T). In actual practice there is always some heat that is radiated out.

Breakdown occurs when $W_{d.c.}$ or $W_{a.c.}$ exceeds W_T . The thermal instability condition is shown in Fig. Here, the heat lost is shown by a straight line, while the heat generated at fields E_1 and E_2 are shown by separate curves. At field E_2 breakdown occurs both at temperatures T_A and T_B . In the temperature region of T_A and T_B heat generated is less than the heat lost for the field E_2 , and hence the breakdown will not occur.

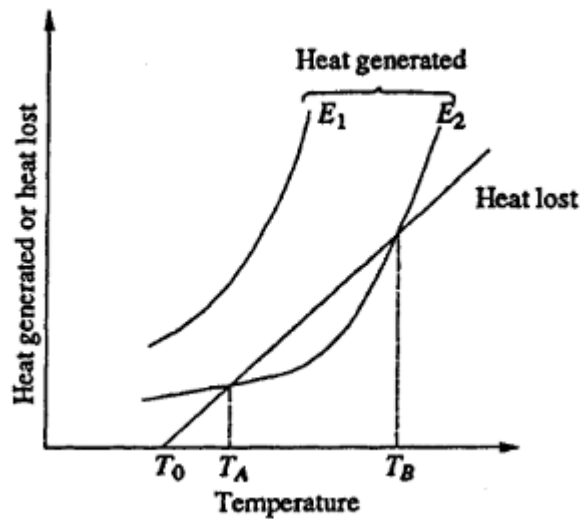


Fig. Thermal instability in solid dielectrics

d) Chemical and Electrochemical Deterioration and Breakdown

In the presence of air and other gases some dielectric materials undergo chemical changes when subjected to continuous electrical stresses. Some of the important chemical reactions that occur are:

Oxidation: In the presence of air or oxygen, materials such as rubber and polyethylene undergo oxidation giving rise to surface cracks.

Hydrolysis: When moisture or water vapour is present on the surface of a solid dielectric, hydrolysis occurs and the materials lose their electrical and mechanical properties. Electrical properties of materials such as paper, cotton tape, and other cellulose materials deteriorate very rapidly due to hydrolysis. Plastics like polyethylene undergo changes, and their service life considerably reduces.

Chemical Action: Even in the absence of electric fields, progressive chemical degradation of insulating materials can occur due to a variety of processes such as chemical instability at high temperatures, oxidation and cracking in the presence of air and ozone, and hydrolysis due to moisture and heat. Since different insulating materials come into contact with each other in any practical apparatus, chemical reactions occur between these various materials leading to reduction in electrical and mechanical strengths resulting in failure.

e) Breakdown Due to Treeing and Tracking

When a solid dielectric subjected to electrical stresses for a long time fails, normally two kinds of visible markings are observed on the dielectric materials.

They are:

- (a) the presence of a conducting path across the surface of the insulation;
- (b) a mechanism whereby leakage current passes through the conducting path finally leading to the formation of a spark. Insulation deterioration occurs as a result of these sparks.

The spreading of spark channels during *tracking*, in the form of the branches of a tree is called *treeing*.

Consider a system of a solid dielectric having a conducting film and two electrodes on its surface. In practice, the conducting film very often is formed due to moisture. On application of voltage, the film starts conducting, resulting in generation of heat, and the surface starts becoming dry. The conducting film becomes separate due to drying, and so sparks are drawn damaging the dielectric surface. With organic insulating materials such as paper and bakelite, the dielectric carbonizes at the region of sparking, and the carbonized regions act as permanent

conducting channels resulting in increased stress over the rest of the region. This is a cumulative process, and insulation failure occurs when carbonized tracks bridge the distance between the electrodes. This phenomena, called **tracking** is common between layers of bakelite, paper and similar dielectrics built of laminates.

Treering occurs due to the erosion of material at the tips of the spark. Erosion results in the roughening of the surfaces, and hence becomes a source of dirt and contamination. This causes increased conductivity resulting either in the formation of a conducting path bridging the electrodes or in a mechanical failure of the dielectric.

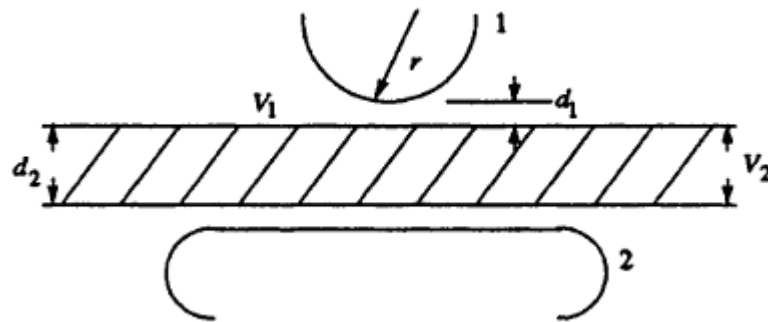


Fig. Arrangement for study of treeing phenomena. 1 and 2 are electrodes

When a dielectric material lies between two electrodes as shown in Fig. there is a possibility for two different dielectric media, the air and the dielectric, to come in series. The voltages across the two media are as shown (V_1 across the air gap, and V_2 across the dielectric). The voltage V_1 across the air gap is given as,

$$V_1 = \frac{V d_1}{d_1 + \left(\frac{\epsilon_1}{\epsilon_2}\right) d_2}$$

where V is the applied voltage.

Since $\epsilon_2 > \epsilon_1$ most of the voltage appears across d_1 the air gap. Sparking will occur in the air gap and, charge accumulation takes place on the surface of the insulation. Sometimes the spark erodes the surface of the insulation. As time passes, breakdown channels spread through the insulation in an irregular "tree" like fashion leading to the formation of conducting channels. This kind of channelling is called treeing.

Under a.c. voltage conditions treeing can occur in a few minutes or several hours. Hence, care must be taken to see that no series air gaps or other weaker insulation gaps are formed.

Usually, tracking occurs even at very low voltages of the order of about 100 V, whereas treeing requires high voltage. For testing of tracking, low and medium voltage tracking tests are specified. These tests are done at low voltages but for times of about 100 hr or more. The insulation should not fail. Sometimes the tests are done using 5 to 10 kV with shorter durations of 4 to 6 hr. The numerical value of voltage that initiates or causes the formation of a track is called the "tracking index" and this is used to qualify the surface properties of dielectric materials.

Treeing can be prevented by having clean, dry, and undamaged surfaces and a clean environment. The materials chosen should be resistant to tracking. Sometimes moisture repellant greases are used. But this needs frequent cleaning and regreasing.

f) Breakdown Due to Internal Discharges

Solid insulating materials, and to a lesser extent liquid dielectrics contain voids or cavities within the medium or at the boundaries between the dielectric and the electrodes. These voids are generally filled with a medium of lower dielectric strength, and the dielectric constant of the medium in the voids is lower than that of the insulation. Hence, the electric field strength in the voids is higher than that across the dielectric. Therefore, even under normal working voltages the field in the voids may exceed their breakdown value, and breakdown may occur.

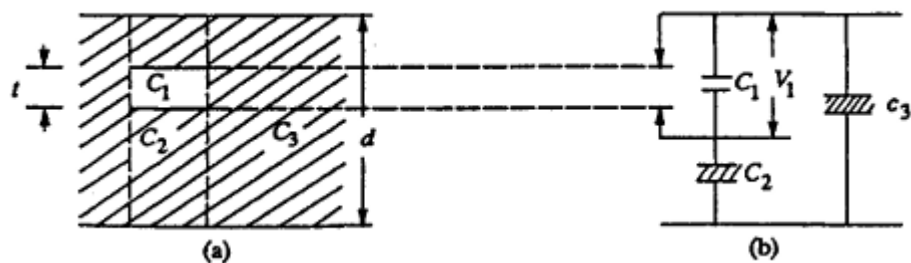


Fig. Electrical discharge in a cavity and its equivalent circuit

C_1 represents the capacitance of the void or cavity, C_2 is the capacitance of the dielectric which is in series with the void, and C_3 is the capacitance of the rest of the dielectric. When the applied voltage is V , the voltage across the void, V_1 is given by the same equation as

$$V_1 = \frac{V d_1}{d_1 + \left(\frac{\epsilon_0}{\epsilon_1}\right) d_2}$$

where d_1 and d_2 are the thickness of the void and the dielectric, respectively, having permittivities ϵ_1 and ϵ_2 .

When a voltage V is applied, V_1 reaches the breakdown strength of the medium in the cavity (V_i) and breakdown occurs. V_i is called the 'discharge inception voltage'. When the applied voltage is a.c., breakdown occurs on both the half cycles and the number of discharges will depend on the applied voltage. The voltage and the discharge current waveforms are shown in Fig.. When the first breakdown across the cavity occurs the breakdown voltage across it becomes zero. When once the voltage V_1 becomes zero, the spark gets extinguished and again the voltage rises till breakdown occurs again. This process repeats again and again, and current pulses as shown, will be obtained both in the positive and negative half cycles.

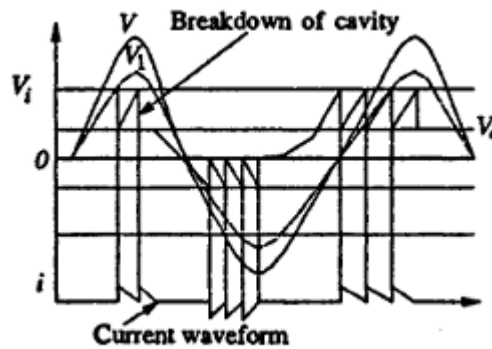


Fig. Sequence of cavity breakdown under alternating voltages

These internal discharges (also called partial discharges) will have the same effect as "treeing" on the insulation. When the breakdown occurs in the voids, electrons and positive ions are formed. They will have sufficient energy and when they reach the void surfaces they may break the chemical bonds. Also, in each discharge there will be some heat dissipated in the cavities, and this will carbonize the surface of the voids and will cause erosion of the material. Channels and pits formed on the cavity surfaces increase the conduction. Chemical degradation may also occur as a result of the active discharge products formed during breakdown.

10. Describe the thermal breakdown mechanism of solid dielectrics. (Dec'11)

Thermal Breakdown

The breakdown voltage of a solid dielectric should increase with its thickness. But this is true only up to a certain thickness above which the heat generated in the dielectric due to the flow of current determines the conduction.

When an electric field is applied to a dielectric, conduction current, however small it may be, flows through the material. The current heats up the specimen and the temperature rises. The heat generated is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces. Equilibrium is reached when the heat used to raise the temperature of the dielectric, plus the heat radiated out, equals the heat generated. The heat generated under d.c. stress E is given as

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where, σ is the d.c. conductivity of the specimen.

Under a.c. fields, the heat generated

$$W_{a.c.} = \frac{E^2 f \epsilon_r \tan \delta}{1.8 \times 10^{12}} \quad \text{W/cm}^3$$

where, f = frequency in Hz,
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The heat dissipated (W_T) is given by

$$W_T = C_V \frac{dT}{dt} + \text{div} (K \text{ grad } T)$$

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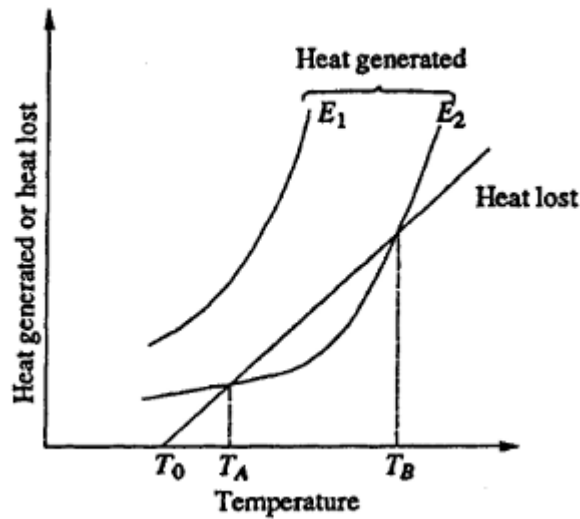


Fig. Thermal instability in solid dielectrics

Breakdown mechanisms in composite dielectrics

11. Discuss about the properties of composite dielectrics.

(May'11)

It is difficult to imagine a complete insulation system in an electrical equipment which does not consist of more than one type of insulation. If an insulation system as a whole is considered, it will be found that more than one insulating material is used. These different materials can be in parallel with each other, such as air or SF_6 gas in parallel with solid insulation or in series with one another. Such insulation systems are called composite dielectrics.

Properties of Composite Dielectrics

A composite dielectric generally consists of a large number of layers arranged one over the other. This is called "the layered construction" and is widely used in cables, capacitors and transformers. Three properties of composite dielectrics which are important to their performance are given below.

(a) *Effect of Multiple Layers*

The simplest composite dielectric consists of two layers of the same material. Here, advantage is taken of the fact that two thin sheets have a higher dielectric strength than a single sheet of the same total thickness. The advantage is particularly significant in the case of materials having a wide variation in dielectric strength values measured at different points on its surface.

(b) Effect of Layer Thickness

Increase in layer thickness normally gives increased breakdown voltage. In a layered construction, breakdown channels occur at the interfaces only and not directly through another layer. Also, a discharge having penetrated one layer cannot enter the next layer until a part of the interface also attains the potential which can produce an electric field stress comparable to that of the discharge channel.

(c) Effect of Interfaces

The interface between two dielectric surfaces in a composite dielectric system plays an important role in determining its pre-breakdown and breakdown strengths. Discharges usually occur at the interfaces and the magnitude of the discharge depends on the associated surface resistance and capacitance. When the surface conductivity increases, the discharge magnitude also increases, resulting in damage to the dielectric.

Mechanisms of Breakdown in Composite Dielectrics

12. Describe the ageing and breakdown in composite dielectrics due to partial discharge.

(Dec'11)

(or)

Explain composite dielectrics and how the breakdown occurs in it? (Dec'12), (Dec'14)

(a) Short-Term Breakdown

If the electric field stresses are very high, failure may occur in seconds or even faster without any substantial damage to the insulating surface prior to breakdown. It has been observed that breakdown results from one or more discharges when the applied voltage is close to the observed breakdown value. There exists a critical stress in the volume of the dielectric at which discharges of a given magnitude can enter the insulation from the surface and propagate rapidly into its volume to cause breakdown. Experiments with single discharges on an insulating material have shown that breakdown occurs more rapidly when the electric field in the insulation is such that it assists the charged particles in the discharge to penetrate into the

insulation, than when the field opposes their entry. Breakdown was observed to occur more readily when the bombarding particles are electrons, rather than positive ions.

(b) Long-Term Breakdown

Long-term breakdown is also called the ageing of insulation. The principal effects responsible for the ageing of the insulation which eventually leads to breakdown arise from the thermal processes and partial discharges. Partial discharges normally occur within the volume of the composite insulation systems. In addition, the charge accumulation and conduction on the surface of the insulation also contributes significantly towards the ageing and failure of insulation.

(i) Ageing and breakdown due to partial discharges

During the manufacture of composite insulation, gas filled cavities will be present within the dielectric or adjacent to the interface between the conductor and the dielectric. When a voltage is applied to such a system, discharges occur within the gas-filled cavities. These discharges are called the "partial discharges" and involve the transfer of electric charge between the two points in sufficient quantity to cause the discharge of the local capacitance. At a given voltage, the impact of this charge on the dielectric surface produces a deterioration of the insulating properties, in many ways, depending on the geometry of the cavity and the nature of the dielectric. The study of breakdown by partial discharges is very important in industrial systems.

(ii) Ageing and breakdown due to accumulation of charges on insulator surfaces

During discharges at the solid or liquid or solid-gas or solid-vacuum interfaces, certain quantity of charge (electrons or positive ions) gets deposited on the solid insulator surface. The charge thus deposited can stay there for very long durations, lasting for days or even weeks. The presence of this charge increases the surface conductivity thereby increasing the discharge magnitude in subsequent discharges. Increased discharge magnitude in subsequent discharges causes damage to the dielectric surface. Experiments using electro-photography and other methods have shown that transverse discharges occur on the faces of the dielectric, and these discharges cause a large area to be discharged instantaneously. Charges that exist in surface conductivity are due to the discharges themselves such that changes in discharge magnitude will occur spontaneously during the life of a dielectric.

UNIT - III -GENERATION AND MEASUREMENTS OF HIGH VOLTAGES AND HIGH CURRENTS

Generation of High DC voltages

1. Explain how high DC voltages produced using rectifier with necessary waveforms and equations.

(or)

Discuss any two methods to produce high DC voltages.

Half and Full Wave Rectifier Circuits

Rectifier circuits for producing high d.c. voltages from a.c. sources may be (a) half wave, (b) full wave, or (c) voltage doubler type rectifiers.

In the half wave rectifier (Fig. a) the capacitor is charged to $V_{\max}$, the maximum a.c. voltage of the secondary of the high voltage transformer in the conducting half cycle. In the other half cycle, the capacitor is discharged into the load. The value of the capacitor C is chosen such that the time constant CR_L is at least 10 times that of the period of the a.c. supply. The rectifier valve must have a peak inverse rating of at least $2 V_{\max}$.

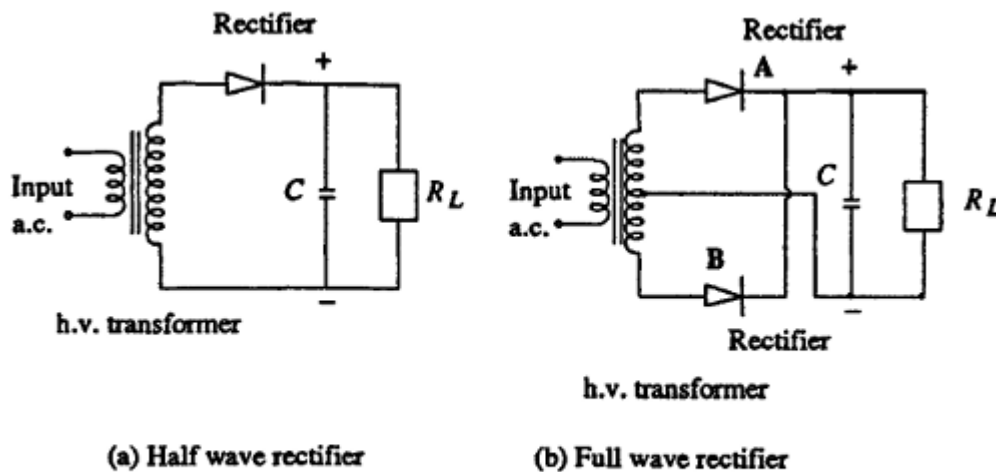


Fig. Full and half wave rectifiers

A full wave rectifier circuit is shown in Fig. b. In the positive half cycle, the rectifier A conducts and charges the capacitor C , while in the negative half cycle the rectifier B conducts and charges the capacitor. The source transformer requires a centre tapped secondary with a rating of $2V$.

Ripple Voltage with Half Wave and Full Wave Rectifiers

When a full wave or a half wave rectifier is used along with the smoothing condenser C , the voltage on no load will be the maximum a.c. voltage. But when on load, the condenser

gets charged from the supply voltage and discharges into load resistance R_L whenever the supply voltage waveform varies from peak value to zero value. These waveforms are shown in Fig. When loaded, a fluctuation in the output d.c. voltage δV appears, and is called a ripple. The ripple voltage δV is larger for a half wave rectifier than that for a full wave rectifier, since the discharge period in the case of half wave rectifier is larger as shown in Fig. The ripple δV depends on (a) the supply voltage frequency f , (b) the time constant CR_L and (c) the reactance of the supply transformer X_L . For half wave rectifiers, the ripple frequency is equal to the supply frequency and for full wave rectifiers, it is twice that value. The ripple voltage is to be kept as low as possible with the proper choice of the filter condenser and the transformer reactance for a given load R_L .

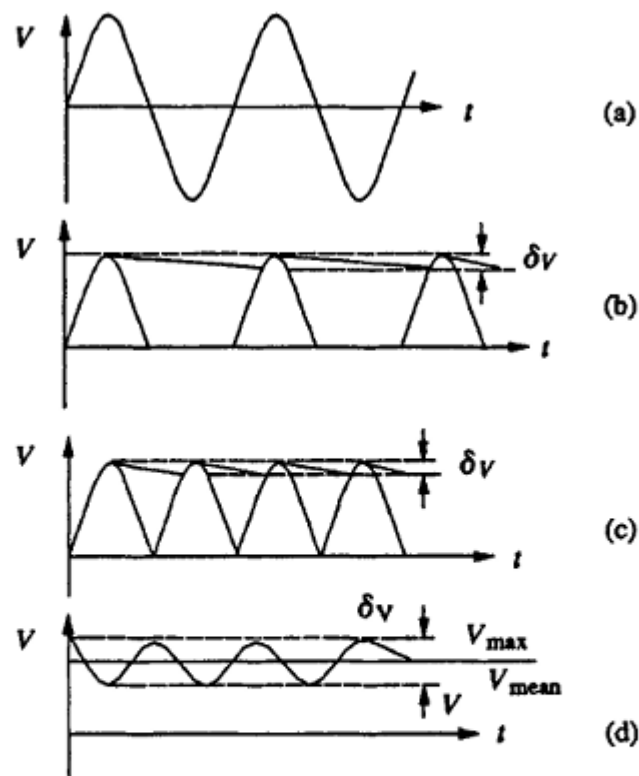


Fig. Input and output waveforms of half and full wave rectifiers

- (a) Input sine wave
- (b) Output with half wave rectifier and condenser filter
- (c) Output with full wave rectifier and condenser filter
- (d) V_{max} , V_{mean} and ripple voltage and δV with condenser filter of a full wave rectifier

Voltage Doubler Circuits

2. Explain the operation of simple voltage doubler circuit.

(Dec'11)

Both full wave and half wave rectifier circuits produce a d.c. voltage less than the a.c. maximum voltage. When higher d.c. voltages are needed, a voltage doubler or cascaded rectifier doubler circuits are used.

In voltage doubler circuit shown in Fig. a, the condenser C_1 is charged through rectifier R_1 to a voltage of $+V_{\max}$ with polarity as shown in the figure during the negative half cycle. As the voltage of the transformer rises to positive $V_{\max}$ during the next half cycle, the potential of the other terminal of C_1 rises to a voltage of $+2V_{\max}$. Thus, the condenser C_2 in turn is charged through R_2 to $2V_{\max}$. Normally the d.c. output voltage on load will be less than $2V_{\max}$, depending on the time constant $C_2 R_L$ and the forward charging time constants.

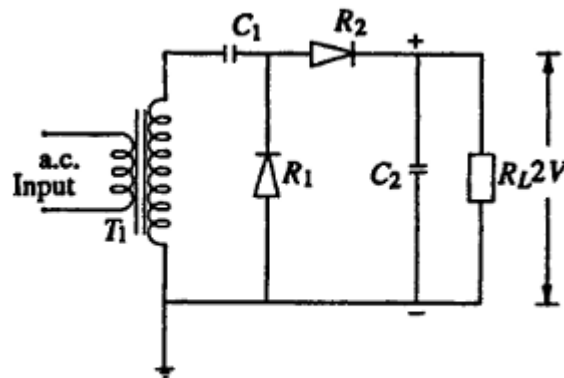


Fig. a Simple voltage doubler

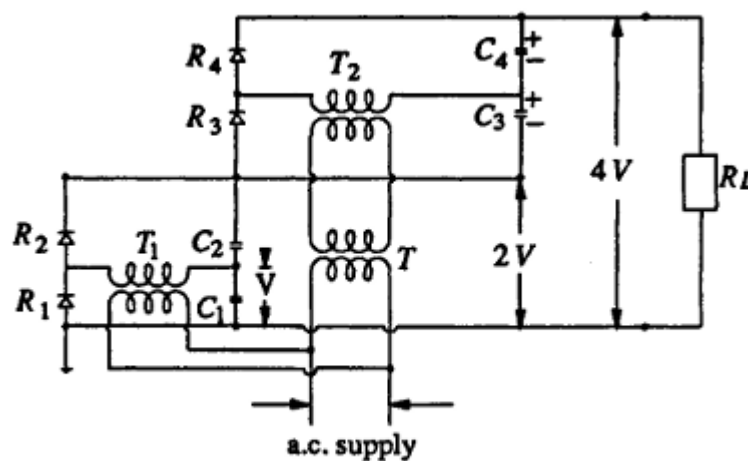


Fig. b Cascaded voltage doubler

Cascaded voltage doublers are used when larger output voltages are needed without changing the input transformer voltage level. A typical voltage doubler is shown in Fig. 6.3b and its input and output waveforms are shown in Fig. c. The rectifiers R_1 and R_2 with transformer T_1 and condensers C_1 and C_2 produce an output voltage of $2V$ in the same way as described above. This circuit is duplicated and connected in series or cascade to obtain a further voltage doubling to $4V$. T is an isolating transformer to give an insulation for $2V_{\max}$ since the transformer T_2 is at a potential of $2V_{\max}$ above the ground. The voltage distribution along the rectifier string R_1, R_2, R_3 and R_4 is made uniform by having condensers C_1, C_2, C_3 and C_4 of equal values. The arrangement may be extended to give $6V, 8V$, and so on by repeating further stages with suitable isolating transformers.

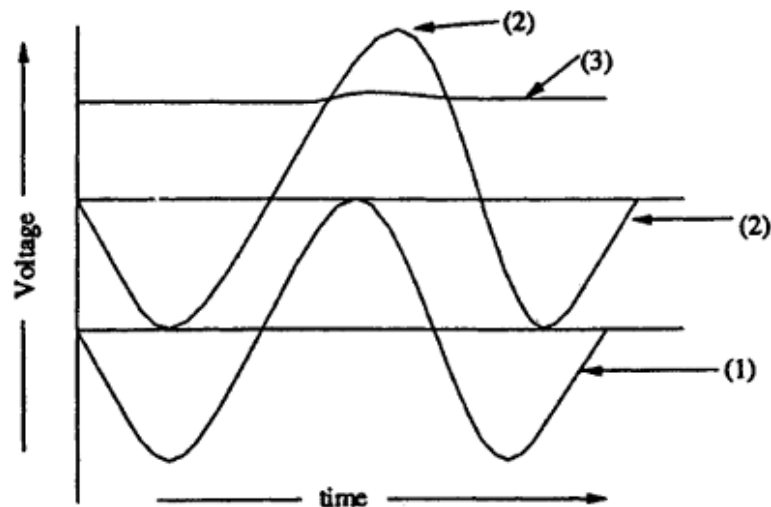


Fig. (c) Waveforms of a.c. voltage and the d.c. output voltage on no-load of the voltage doubler shown in Fig. 6.3 (b)

(1) a.c input voltage waveform, (2) a.c. output voltage waveform without condenser filter, (3) a.c. output voltage waveform with condenser filter

Fig. Voltage doubler circuits

T_1, T_2 – h.v. transformers; R_1, R_2, R_3, R_4 – rectifiers;
 C_1, C_2, C_3 – condensers; R_L – Load resistance; T – isolating transformer

Voltage Multiplier Circuits

3. With neat sketch explain the working principle of a Cockcroft – Walton voltage multiplier circuits.

(Dec'13) , (May'14) , (Dec'14) (Dec'19)

(or)

What are the different forms of high voltages classified? Explain any one method of voltage multiplier circuits.

Cascaded voltage multiplier circuits for higher voltages are cumbersome and require too many supply and isolating transformers. It is possible to generate very high d.c. voltages from single supply transformers by extending the simple voltage doubler circuits. This is simple and compact when the load current requirement is less than one milliamper, such as for cathode ray tubes, etc.

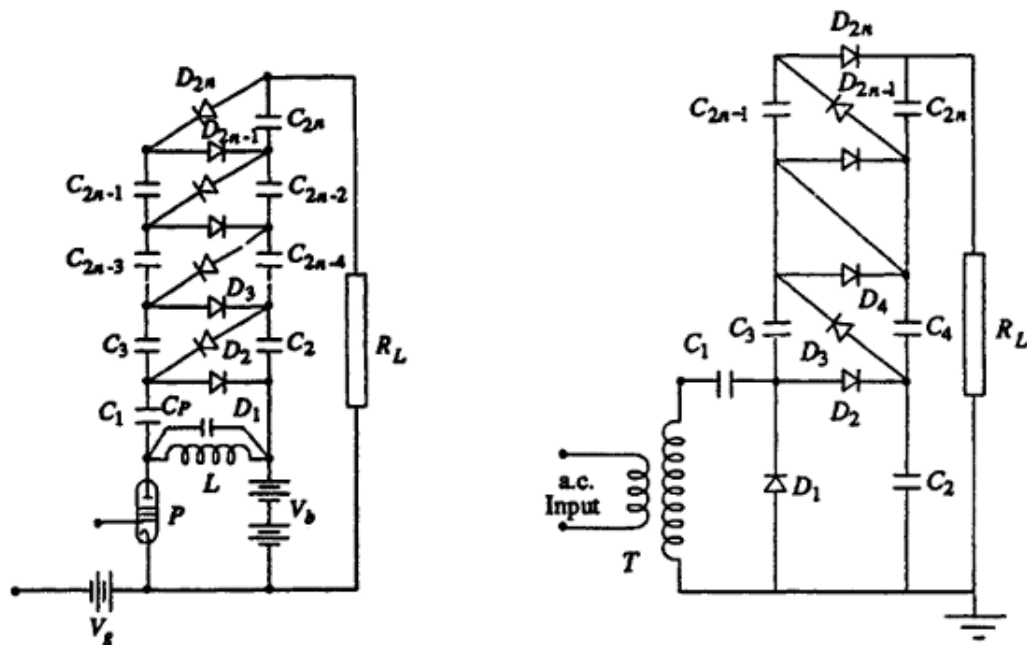


Fig. a Cascaded rectifier unit with pulse generator
 P — Pulse generator
 V_b — D.C. supply to pulse generator
 V_g — Bias voltage

Fig. b Cockcroft-Walton voltage multiplier circuit

Voltage multiplier circuit using the Cockcroft-Walton principle is shown in Fig.b. The first stage, i.e. D_1, D_2, C_1, C_2 , and the transformer T are identical as in the voltage doubler shown in Fig. For higher output voltage of $4.6, \dots, 2n$ of the input voltage V the circuit is repeated with cascade or series connection. Thus, the condenser C_4 is charged to $4V_{\max}$ and C_{2n} to $2nV_{\max}$ above the earth potential. But the volt across any individual condenser or rectifier is only $2V_{\max}$.

The rectifiers $D_1, D_3, \dots, D_{2n-1}$ shown in Fig. b operate and conduct during the positive half cycles while the rectifiers $D_2, D_4, \dots, D_{2n}$ conduct during the negative half cycles. Typical

current and voltage waveforms of such a circuit are shown in Figs. c and d respectively. The voltage on C_2 is the sum of the input a.c. voltage, V_{ac} and the voltage across condenser C_1, V_{C1} as shown in Fig. The mean voltage on C_2 is less than the positive peak charging voltage ($V_{ac} + V_{C1}$). The voltages across other condensers C_2 to C_{2n} can be derived in the same manner, (i.e.) from the difference between voltage across the previous condenser and the charging voltage. Finally the voltage after $2n$ stages will be $V_{ac} (n_1 + n_2 + \dots)$, where $n_1, n_2, \dots$ are factors when ripple and regulation are considered in the next rectifier.

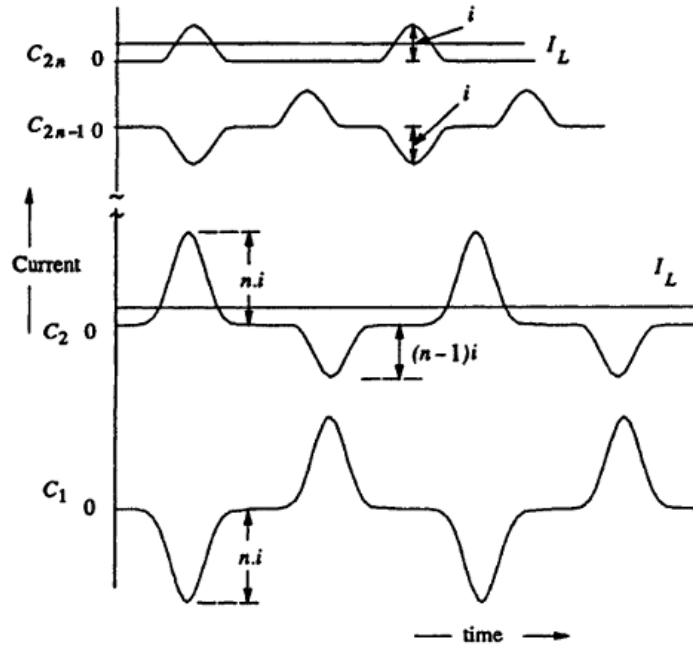


Fig. c Schematic current waveforms across the first and the last capacitors of the cascaded voltage multiplier circuit shown in Fig. (b)

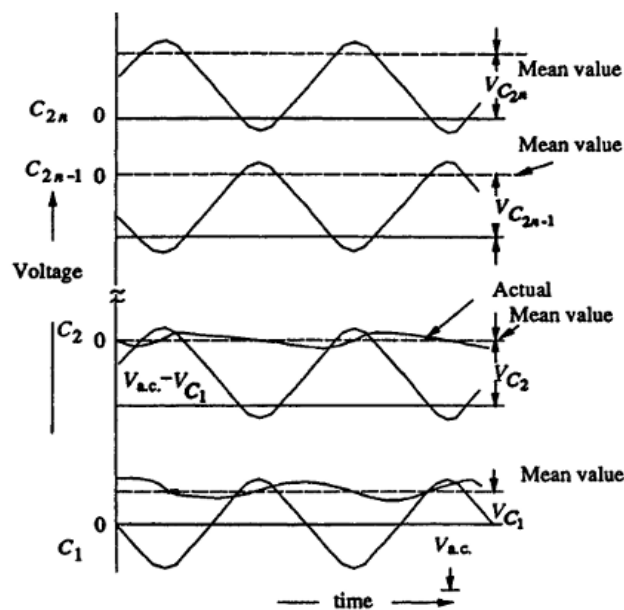


Fig. d Voltage waveforms across the first and the last capacitors of the cascaded voltage multiplier circuit shown in Fig. (b)

Ripple In Cascaded Voltage Multiplier Circuits

Let f - supply frequency,

q = charge transferred in each cycle,

I_1 = load current from the rectifier,

t_1 = conduction period of the rectifiers

t_2 = non-conduction period of rectifiers, and

δV = ripple voltage.

Referring to Fig. a, when load current I_1 is supplied from condenser C_2 to load R_L during the non-conducting period, the charge transferred per cycle from the condenser C_2 to the load during the non-conduction period t_2 is q , and is related as follows.

$$I_1 = \frac{dq}{dt} \approx \frac{q}{t_2}$$

Since $t_1 \ll t_2$ and $t_1 + t_2 = \frac{1}{f}$ (i.e. the period of these a.c. supply voltage),

$$t_2 = \frac{1}{f}$$

Also,

$$q = C_2 \delta V$$

Hence,

$$\delta V = \text{the ripple} = \frac{I_1}{fC_2}$$

At the same time a charge q is transferred from C_1 to C_2 during each cycle of

$$x = \frac{I_1}{fC_2}.$$

Hence, regulation = mean voltage drop from $2V_{\max}$

$$= \frac{I_1}{f} \left[\frac{1}{C_1} + \frac{1}{2C_2} \right]$$

Therefore, the mean output voltage = $2V_{\max} - \frac{I_1}{f} \left(\frac{1}{C_1} + \frac{1}{2C_2} \right)$.

Referring to Fig. b, to find an expression for the total ripple voltage, let it be assumed that all capacitances $C_1, C_2, \dots, C_{2n}$ be equal to C . Let q be the charge transferred from C_{2n} to the load per cycle.

Then the ripple at the condenser C_{2n} will be $\frac{I_1}{fC}$.

Simultaneously, C_{2n-2} transfers as charge q to the load and to C_{2n-1} .

Hence, the ripple at the condenser C_{2n-2} is $\frac{2I_1}{fC}$.

Similarly, C_{2n-4} transfers a charge q to the load, to C_{2n-3} , and to C_{2n-2} .

Therefore, the ripple at condenser C_{2n-4} is $\frac{3I_1}{fC}$.

Proceeding in the same way, the ripple at C_2 will be $\frac{nI_1}{fC}$.

Hence, for n stages the total ripple will be

$$\delta V_{\text{total}} = \frac{I_1}{fC} [1 + 2 + 3 \dots + n] = \frac{I_1}{fC} \frac{n(n+1)}{2}.$$

It can be seen from the above expression that the lowest capacitances (C_2, C_4 , etc.) contribute most for the ripple. If these capacitances are increased proportionately, i.e. C_1 and C_2 are made equal to nC , C_3 and C_4 are made equal to $(n-1)C$ and so on, the total ripple will be only $\frac{nI_1}{fC}$.

Electrostatic Machines: Basic Principle

In electromagnetic machines, current carrying conductors are moved in a magnetic field, so that the mechanical energy is converted into electrical energy. In electrostatic machines charged bodies are moved in an electric field against an electrostatic field in order that mechanical energy is converted into electrical energy. Thus, if an insulated belt with a charge density δ moves in an electric field $E(x)$ between two electrodes with separation 's' then (i) the charge on the strip of belt at a distance dx is $dq = \delta b \cdot dx$ where b is the width of the belt, and

(ii) the force on the belt, F is

$$F = \int_0^s E(x) \cdot dq = \int_0^s \delta \cdot b \cdot E(x) dx$$

If the belt moves with a velocity, v , then the mechanical power P , required to move

the belt is $P = F \cdot v = \delta \cdot b \cdot v \int_0^s E(x) dx$

The current, I , in the system is given as

$$I = dq/dt = \delta \cdot b \cdot dx/dt = \delta \cdot b \cdot v$$

and the potential difference, V , between the electrodes is

$$V = \int_0^s E(x) dx$$

Thus, in an electrostatic machine, the mechanical power required to move the belt at a velocity v , i.e. $P = F \cdot v$ is converted into the electrical power, $P = V \cdot I$, assuming that there are no losses in the system. The Van de Graaff generator is one such electrostatic machine which generates very high voltages, with small output current.

Van de Graaff Generators

4. Discuss the principle of operation of vande graff generator with neat sketch. (Dec'11)

The generator is usually enclosed in an earthed metallic cylindrical vessel and is operated under pressure or in vacuum. Charge is sprayed on to an insulating moving belt from corona points at a potential of 10 to 100 kV above earth and is removed and collected from the belt connected to the inside of an insulated metal electrode through which the belt moves. The belt is driven by an electric motor at a speed of 1000 to 2000 metres per minute. The potential of the high voltage electrode above the earth at any instant is $V = Q/C$ where Q is the charge stored and C is the capacitance of the high voltage electrode to earth. The potential of the high voltage electrode rises at a rate

$$\frac{dV}{dt} = \frac{1}{C} \frac{dQ}{dt} = \frac{I}{C} \quad \text{where } I \text{ is the net charging current.}$$

The charging of the belt is done by the lower spray points which are sharp needles and connected to a d.c. source of about 10 to 100 kV, so that the corona is maintained between the moving belt and the needles. The charge from the corona points is collected by the collecting needles from the belt and is transferred on to the high voltage electrode as the belt enters into the high voltage electrode. The belt returns with the charge dropped, and fresh charge is sprayed on to it as it passes through the lower corona point. Usually in order to make the charging more effective and to utilize the return path of the belt for charging purposes, a self-inducing arrangement or a second corona point system excited by a rectifier inside the high voltage terminal is employed. To obtain a self-charging system, the upper pulley is connected to the collector needle and is therefore maintained at a potential higher than that of the high voltage terminal. Thus a second row of corona points connected to the inside of the high voltage terminal and directed towards the pulley above its point of entry into the terminal gives a corona discharge to the belt. This neutralizes any charge on the belt and leaves an excess of opposite polarity to the terminal to travel down with the belt to the bottom charging point. Thus, for a given belt speed the rate of charging is doubled.

Van de Graaff generators are useful for very high voltage and low current applications. The *output* voltage is easily controlled by controlling the corona source voltage and the rate of charging. These are extremely flexible and precise machines for voltage control.

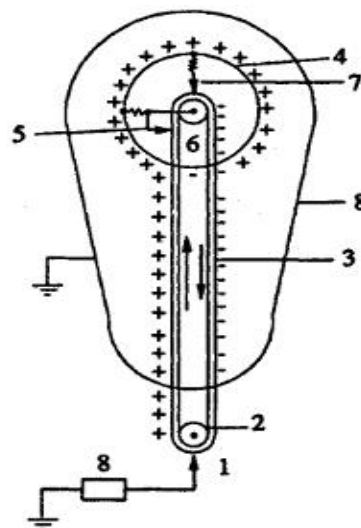


Fig. Van de Graaff generator

1. Lower spray point
2. Motor driven pulley
3. Insulated belt
4. High voltage terminal
5. Collector
6. Upper pulley insulated from terminal
7. Upper spray point
8. Earthed enclosure

Electrostatic Generators

5. Explain the basic principle of operation of an electrostatic generator. (May'11)

(or)

Explain in detail about Electrostatic generators. (Dec'12)

Van de Graaff generators are essentially high voltage but low power devices, and their power rating seldom exceeds few tens of kilowatts. As such electrostatic machines which effectively convert mechanical energy into electrical energy using variable capacitor principle were developed. These are essentially duals of electromagnetic machines and are constant voltage variable capacitance machines. An electrostatic generator consists of a stator with interleaved rotor vanes forming a variable capacitor and operates in vacuum.

The current through a variable capacitor is given by $I = \frac{dV}{Cdt} + V \frac{dC}{dt}$ where C is a

capacitor charged to a potential V.

The power input into the circuit at any instant is

$$P = VI = CV \frac{dV}{Cdt} + V^2 \frac{dC}{dt}$$

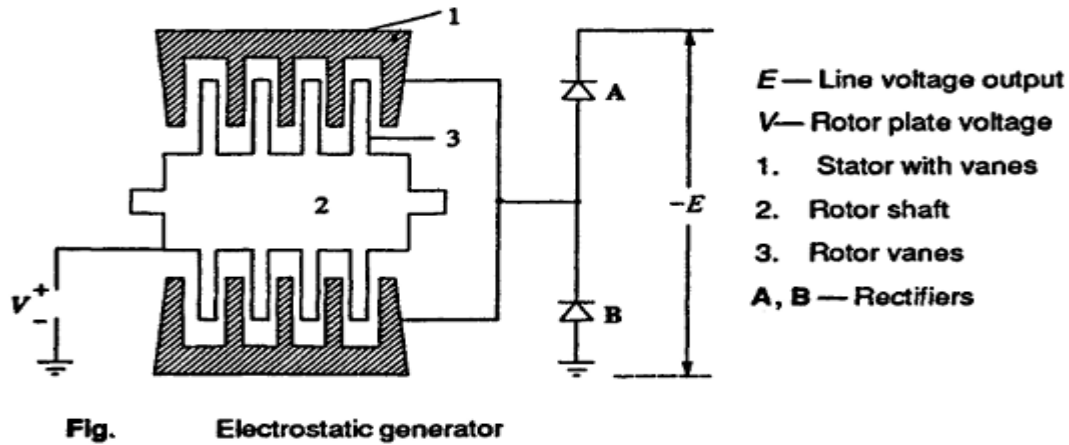
If $\frac{dC}{dt}$ is negative, mechanical energy is converted into electrical energy.

With the capacitor charged with a d.c. voltage V, $\frac{dV}{dt} = 0$ and the power output will be $P = V^2 \frac{dC}{dt}$.

The rotor is insulated from the ground, and is maintained at a potential of + V. The rotor to stator capacitance varies from C_0 to C_m , and the stator is connected to a common point between two rectifiers across the d.c. output which is -E volts. When the capacitance of the rotor is maximum (C_m), the rectifier B does not conduct and the stator is at ground potential. The potential E is applied across the rectifier A and V is applied across C_m . As the rotor rotates, the capacitance C decreases and the voltage across C increases.

Thus, the stator becomes more negative with respect to ground. When the stator reaches the line potential -E the rectifier A conducts, and further movement of the rotor causes the current to flow from the generator. Rectifier B will now have E across it and the charge left in the generator will be $Q_0 = C_0 (V+E) + E(C_s + C_r)$, where C_s is the stator capacitance to earth,

C_r is the capacitance of rectifier B to earth, and C_o is the minimum capacitance value of C (stator to rotor capacitance).



Generation of High Alternating voltages

6. Explain any one method of generating HV AC at power frequency and discuss its limitation/feature.

(or)

Describe the cascade transformer connection to generate high alternating voltages.

(Dec'13)

When test voltage requirements are less than about 300 kV, a single transformer can be used for test purposes. For higher voltage requirements, a single unit construction becomes difficult and costly due to insulation problems. Moreover, transportation and erection of large transformers become difficult. These drawbacks are overcome by series connection or cascading of the several identical units of transformers, wherein the high voltage windings of all the units effectively come in series.

Cascade Transformers

Figure shows the cascade transformer units in which the first transformer is at the ground potential along with its tank. The second transformer is kept on insulators and maintained at a potential of V_2 , the output voltage of the first unit above the ground. The high voltage winding of the first unit is connected to the tank of the second unit. The low voltage winding of this unit is supplied from the excitation winding of the first transformer, which is in series with the high voltage winding of the first transformer at its high voltage end. The rating of the excitation winding is almost identical to that of the primary or the low voltage

winding. The high voltage connection from the first transformer winding and the excitation winding terminal are taken through a bushing to the second transformer. In a similar manner, the third transformer is kept on insulators above the ground at a potential of $2V_2$ and is supplied likewise from the second transformer. The number of stages in this type of arrangement are usually two to four.

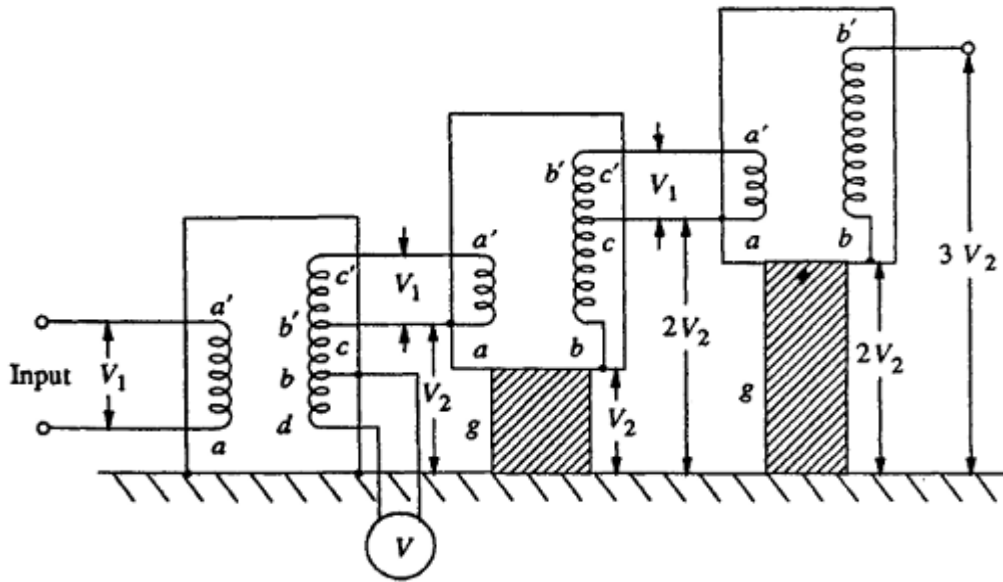


Fig. Cascade transformer connection (schematic)

- V_1 — Input voltage
- V_2 — Output voltage
- aa' — L.V. primary winding
- bb' — H.V. secondary winding
- cc' — Excitation winding
- bd — Meter winding (200 to 500 V)

In Fig., a second scheme for providing the excitation to the second and the third stages is shown. Isolating transformers I_{s1} , I_{s2} and I_{s3} are 1:1 ratio transformers insulated to their respective tank potentials and are meant for supplying the excitation for the second and the third stages at their tank potentials. Power supply to the isolating transformers is also fed from the same a.c. input. This scheme is expensive and requires more space. The advantage of this scheme is that the natural cooling is sufficient and the transformers are light and compact. Transportation and assembly is easy. Also the construction is identical for isolating transformers and the high voltage cascade units. Three phase connection in delta or star is possible for three units. Testing transformers of ratings up to 10 MVA in cascade connection to give high voltages up to 2.25 MV are available for both indoor and outdoor applications.

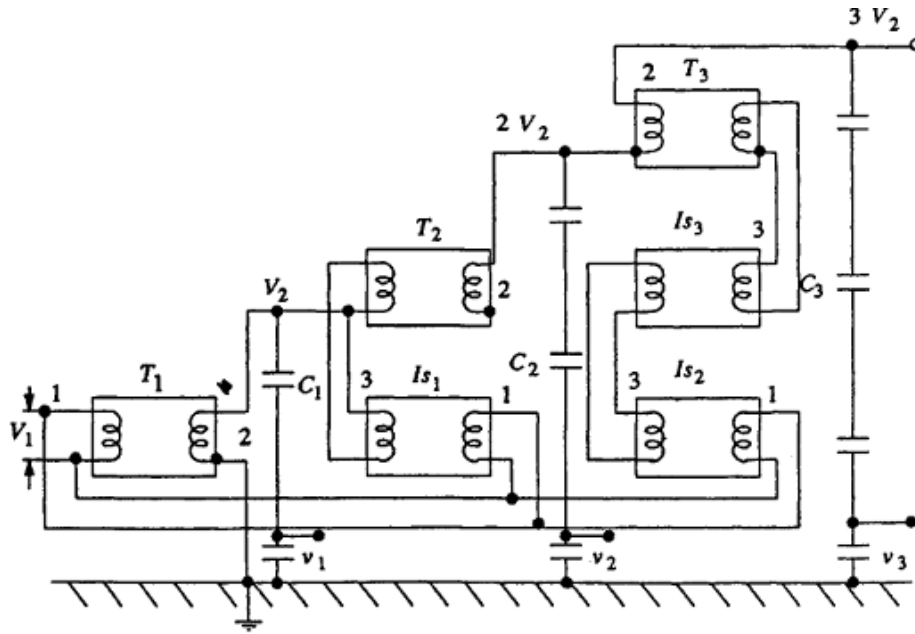


Fig. Cascade transformer unit with isolating transformers for excitation

T_1, T_2, T_3 — Cascade transformer units
 Is_1, Is_2, Is_3 — Isolation transformer units
 C_1, C_2, C_3 — Capacitance voltage dividers for h.v. measurement after 1st, 2nd and 3rd stages
 V_1, V_2, V_3 — For metering after 1st, 2nd and 3rd stages
 1. Primary (l.v. winding), 2.h.v. winding, 3. Excitation winding.

Resonant Transformers

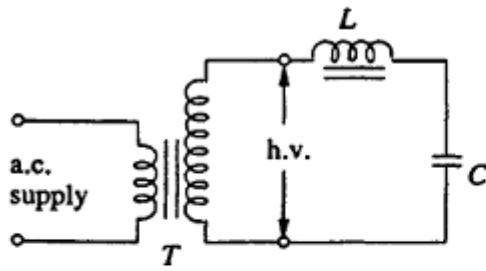
7. Write a brief note on resonant transformer method.

(Dec'11)

The equivalent circuit of a high voltage testing transformer consists of the leakage reactances of the windings, the winding resistances, the magnetizing reactance, and the shunt capacitance across the output terminal due to the bushing of the high voltage terminal and also that of the test object. This is shown in Fig. (a) with its equivalent circuit in Fig (b). It may be seen that it is possible to have series resonance at power frequency ω , if $(L_1 + L_2) = 1/\omega C$. With this condition, the current in the test object is very large and is limited only by the resistance of the circuit. The waveform of the voltage across the test object will be purely sinusoidal. The magnitude of the voltage across the capacitance C of the test object will be

$$V_C = \left| \frac{-jVX_C}{R+j(X_L-X_C)} \right| = \frac{V}{R} X_C = \frac{V}{\omega CR}$$

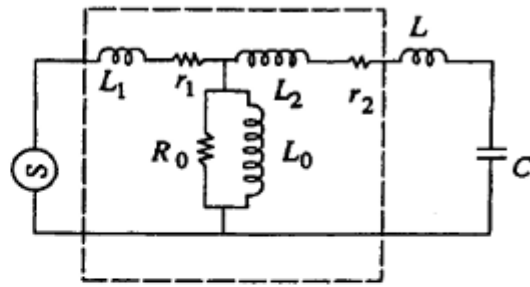
where R is the total series resistance of the circuit.



(a)

Fig. a Transformer

T — Testing transformer
L — Choke
C — Capacitance of h.v. terminal and test object
L₀ — Magnetizing inductance



(b)

Fig. b Equivalent circuit

L₁, L₂ — Leakage inductances of the transformer
r₁, r₂ — Resistances of the windings
R₀ — Resistance due to core loss

The factor $X_c/R = 1/\omega CR$ is the Q factor of the circuit and gives the magnitude of the voltage multiplication across the test object under resonance conditions. Therefore, the input voltage required for excitation is reduced by a factor $1/Q$, and the output kVA required is also reduced by a factor $1/Q$. The secondary power factor of the circuit is unity.

This principle is utilized in testing at very high voltages and on occasions requiring large current outputs such as cable testing, dielectric loss measurements, partial discharge measurements, etc. A transformer with 50 to 100 kV voltage rating and a relatively large current rating is connected together with an additional choke, if necessary. The test condition is set such that $\omega(L_e + L) = 1/\omega C$ where L_e is the total equivalent leakage inductance of the transformer including its regulating transformer. The chief advantages of this principle are:

- (a) it gives an output of pure sine wave,
- (b) power requirements are less (5 to 10% of total kVA required),
- (c) no high-power arcing and heavy current surges occur if the test object fails, as resonance ceases at the failure of the test object,
- (d) cascading is also possible for very high voltages,
- (e) simple and compact test arrangement, and
- (f) no repeated flashovers occur in case of partial failures of the test object and insulation recovery. It can be shown that the supply source takes Q number of cycles at least to charge the test specimen to the full voltage.

The disadvantages are the requirements of additional variable chokes capable of withstanding the full test voltage and the full current rating.

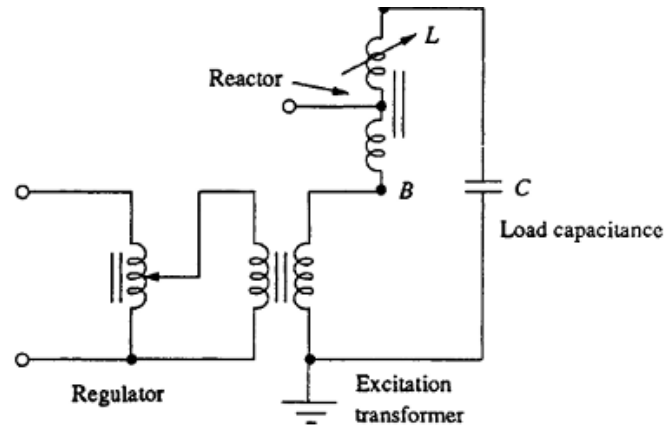


Fig. c Series resonant a.c. test system

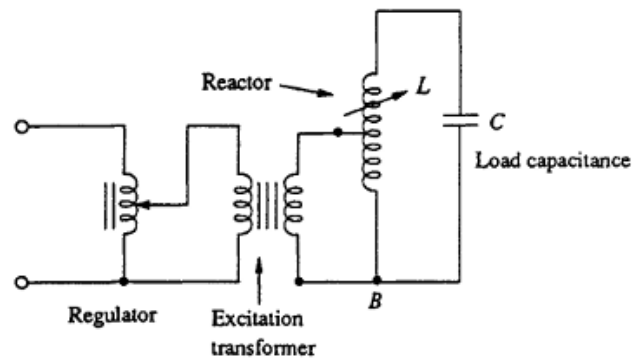


Fig. d Parallel resonant a.c. test system

A voltage regulator of either the auto-transformer type or the induction regulator type is connected to the supply mains and the secondary winding of the exciter transformer is connected across the H.V. reactor, L , and the capacitive load C . The inductance of the reactor L is varied by varying its air gap and operating range is set in the ratio 10 : 1. Capacitance C comprises of the capacitance of the test object, capacitance of the measuring voltage divider, capacitance of the high voltage bushing etc. The Q-factor obtained in these circuits will be typically of the order of 50. In the parallel resonant mode the high voltage reactor is connected as an auto-transformer and the circuit is connected as a parallel resonant circuit. The advantage of the parallel resonant circuit is that more stable output voltage can be obtained along with a high rate of rise of test voltage, independent of the degree of tuning and the Q-factor.

Generation of High Frequency a.c. High Voltages

8. What is Tesla coil? How are damped high frequency oscillations obtained from a Tesla coil?

(Dec'17) (Dec'12), (Dec'14)

High frequency high voltages are required for rectifier d.c. power supplies. Also, for testing electrical apparatus for switching surges, high frequency high voltage damped oscillations are needed which need high voltage high frequency transformers. The advantages of these high frequency transformers are:

- (i) the absence of iron core in transformers and hence saving in cost and size,
- (ii) pure sine wave output,
- (iii) slow build-up of voltage over a few cycles and hence no damage due to switching surges, and
- (iv) uniform distribution of voltage across the winding coils due to subdivision of coil stack into a number of units.

The commonly used high frequency resonant transformer is the Tesla coil, which is a doubly tuned resonant circuit shown schematically in Fig. a. The primary voltage rating is 10 kV and the secondary may be rated to as high as 500 to 1000 kV. The primary is fed from a d.c. or a.c. supply through the condenser C_1 . A spark gap G connected across the primary is triggered at the desired voltage V_1 which induces a high self-excitation in the secondary. The primary and the secondary windings (L_1 and L_2) are wound on an insulated former with no core (air-cored) and are immersed in oil. The windings are tuned to a frequency of 10 to 100 kHz by means of the condensers C_1 and C_2 .

The output voltage V_2 is a function of the parameters L_1 , L_2 , C_1 , C_2 and the mutual inductance M . Usually, the winding resistances will be small and contribute only for damping of the oscillations.

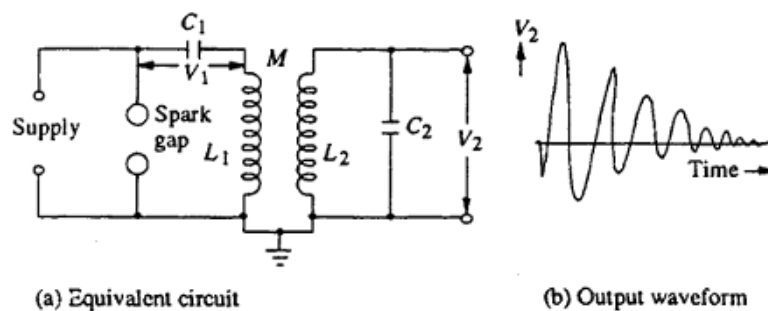


Fig. Tesla coil equivalent circuit and its output waveform

Analysis of the output waveform

The analysis of the output waveform can be done in a simple manner neglecting the winding resistances. Let the condenser C_1 be charged to a voltage V_1 when the spark gap is triggered. Let a current i_1 flow through the primary winding L_1 and produce a current i_2 through L_2 and C_2

Then,

$$V_1 = \frac{1}{C_1} \int_0^t i_1 dt + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt}$$

and,

$$0 = \frac{1}{C_2} \int_0^t i_2 dt + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}$$

The Laplace transformed equations for the above are,

$$\frac{V_1}{s} = \left[L_1 s + \frac{1}{C_1 s} \right] I_1 + M s I_2$$

and,

$$0 = [M s] I_1 + \left[L_2 s + \frac{1}{C_2 s} \right] I_2$$

where I_1 and I_2 are the Laplace transformed values, of i_1 and i_2 .

The output voltage V_2 across the condenser C_2 is

$$V_2 = \frac{1}{C_2} \int_0^t i_2 dt; \text{ or its transformed equation is}$$

$$V_2(s) = \frac{I_2}{C_2 s}$$

where $V_2(s)$ is the Laplace transform of V_2 .

The solution for V_2 from the above equations will be

$$V_2 = \frac{M V_1}{\sigma L_1 L_2 C_1} \frac{1}{\gamma_2^2 - \gamma_1^2} [\cos \gamma_1 t - \cos \gamma_2 t]$$

where,

$$\sigma^2 = 1 - \frac{M^2}{L_1 L_2} = 1 - K^2$$

K = coefficient of coupling between the windings L_1 and L_2

$$\gamma_{1,2} = \frac{\omega_1^2 + \omega_2^2}{2} \pm \sqrt{\left(\frac{\omega_1^2 + \omega_2^2}{2} \right)^2 - \omega_1^2 \omega_2^2 (1 - K^2)}$$

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}} \text{ and } \omega_2 = \frac{1}{\sqrt{L_2 C_2}}$$

The peak amplitude of the secondary voltage V_2 can be expressed as,

$$V_{2\max} = V_1 e \sqrt{\frac{L_2}{L_1}}$$

where,

$$e = \frac{2\sqrt{(1-\sigma)}}{\sqrt{(1+a)^2 - 4\sigma a}}$$

$$a = \frac{L_2 C_2}{L_1 C_1} = \frac{W_1^2}{W_2^2}$$

A more simplified analysis for the Tesla coil may be presented by considering that the energy stored in the primary circuit in the capacitance C_1 is transferred to C_2 via the magnetic coupling. If W_1 is the energy stored in C_1 and W_2 is the energy transferred to C_2 and if the efficiency of the transformer is η , then

$$W_1 = \frac{1}{2} \eta C_1 V_1^2 = \left(\frac{1}{2} C_2 V_2^2\right)$$

from which
$$V_2 = V_1 \sqrt{\eta \frac{C_1}{C_2}}$$

It can be shown that if the coefficient of coupling K is large the oscillation frequency is less, and for large values of the winding resistances and K , the waveform may become a unidirectional impulse.

Generation of impulse voltages

Standard Impulse Waveshapes

Impulse waves are specified by defining their rise or front time, fall or tail time to 50% peak value, and the value of the peak voltage. Thus 1.2/50 μ s, 1000 kV wave represents an impulse voltage wave with a front time of 1.2 μ s, fall time to 50% peak value of 50 μ s, and a peak value of 1000 kV.

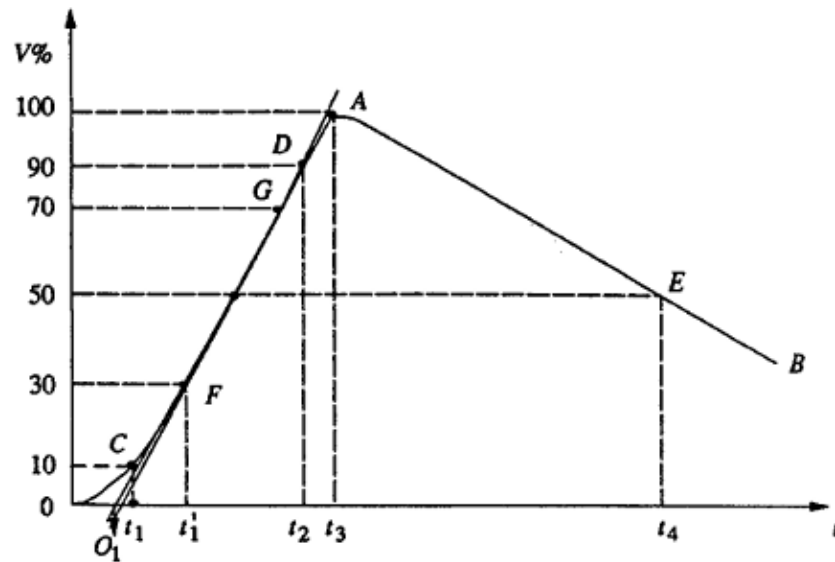


Fig. Impulse waveform

The points corresponding to 10% and 90% of the peak values are located in the front portion (points C and D). The line joining these points is extended to cut the time axis at O_1 . O_1 is taken as the virtual origin. 1.25 times the interval between times t_1 and t_2 corresponding to points C and D (projections on the time axis) is defined as the front time, i.e. $1.25 (O_1 t_2 - O_1 t_1)$. The point E is located on the wave tail corresponding to 50% of the peak value, and its projection on the time axis is t_4 . $O t_4$ is defined as the fall or tail time.

Circuits for Producing Impulse Waves

9. Draw and explain the circuits for producing impulse waves. (May'14)

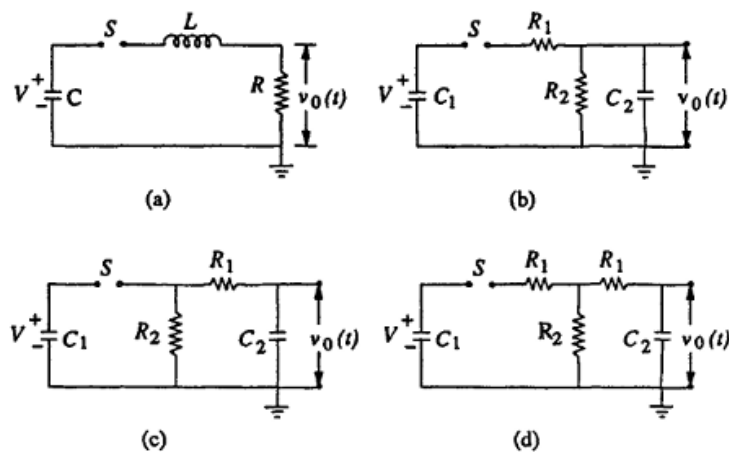


Fig. Circuits for producing impulse waves

Analysis of Impulse Generator Circuit of Series R-L-C Type

Referring to Fig. the current through the load resistance R is given by

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

with initial condition at $t = 0$ being $i(0) = 0$ and the net charge in the circuit $i = dq/dt = 0$. Writing the above equation as a Laplace transform equation,

$$V/s = \left(\frac{1}{Cs} + R + Ls \right) I(s)$$

or,

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

The voltage across the resistor R (which is the output voltage) is, $v_0(s) = I(s) R$; hence,

$$v_0(s) = V \frac{R}{L} \frac{1}{s^2 + \frac{Rs}{L} + \frac{1}{LC}}$$

For an overdamped condition, $R/2L \geq 1/\sqrt{LC}$

Hence, the roots of the equation $s^2 + \frac{Rs}{L} + \frac{1}{LC}$ are

$$\alpha = s_1 = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

$$\beta = s_2 = -\frac{R}{2L} - \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

The solution of the equation for $v_0(t)$ is

$$\begin{aligned} v_0(t) &= \frac{V \left(\frac{R}{2L} \right)}{\left[\frac{R^2}{4L^2} - \frac{1}{LC} \right]^{\frac{1}{2}}} [\exp(-\alpha t) - \exp(-\beta t)] \\ &= V_0 [\exp(-\alpha t) - \exp(-\beta t)] \end{aligned}$$

where,

$$V_0 = \frac{V \left(\frac{R}{2L} \right)}{\left[\frac{R^2}{4L^2} - \frac{1}{LC} \right]^{\frac{1}{2}}} = \frac{V}{\left[1 - \frac{4L}{CR^2} \right]^{\frac{1}{2}}}$$

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

and, the product of the roots $\alpha\beta = \frac{1}{LC}$

The wave front and the wave tail times are controlled by changing the values of R and L simultaneously with a given generator capacitance C ; choosing a suitable value for L . β or the wave front time is determined and α or the wave tail time is controlled by the value of R in the circuit. The advantage of this circuit is its simplicity. But the wave shape control is not flexible and independent. Another disadvantage is that the basic circuit is altered when a test object which will be mainly capacitive in nature, is connected across the output. Hence, the waveshape gets changed with the change of test object.

Analysis of the Other Impulse Generator Circuits

The most commonly used configurations for impulse generators are the circuits shown in Figs. b and c. The advantages of these circuits are that the wave front and wave tail times are independently controlled by changing either R_1 or R_2 separately. Secondly, the test objects which are mainly capacitive in nature form part of C_2 .

For the configuration shown in Fig. b, the output voltage across C_2 is given

$$\text{by, } v_0(t) = \frac{1}{C_2} \int_0^t i_2 dt.$$

Performing Laplace transformation, $\frac{1}{C_2 s} I_2(s) = v_0(s)$

where i_2 is the current through C_2 .

Taking the current through C_1 as i_1 and its transformed value as $I_1(s)$,

$$I_2(s) = \left[\frac{R_2}{R_2 + \frac{1}{C_2 s}} \right] I_1(s)$$

$$I_1(s) = \frac{V}{s} \frac{1}{\frac{1}{C_1 s} + R_1 + \frac{R_2 \cdot \frac{1}{C_2 s}}{R_2 + \frac{1}{C_2 s}}}$$

where, $\frac{R_2 \cdot \frac{1}{C_2 s}}{R_2 + \frac{1}{C_2 s}}$ represents the impedance of the parallel combination of R_2 and C_2 .

Substitution of $I_1(s)$ gives

$$v_0(s) = \frac{1}{C_2 s} \cdot \frac{R_2}{R_2 + \frac{1}{C_2 s}} \cdot \frac{V}{s} \cdot \frac{1}{\frac{1}{C_1 s} + R_1 + \frac{R_2(1/C_2 s)}{R_2 + (1/C_2 s)}}$$

After simplification and rearrangement,

$$v_0(s) = \frac{V}{R_1 C_2} \left[\frac{1}{s^2 + \left(\frac{1}{C_1 R_1} + \frac{1}{C_2 R_2} + \frac{1}{C_2 R_1} \right) s + \frac{1}{C_1 C_2 R_1 R_2}} \right]$$

Hence, the roots of the equation

$$s^2 + \left[\frac{1}{C_1 R_1} + \frac{1}{C_2 R_2} + \frac{1}{C_2 R_1} \right] s + \frac{1}{C_1 C_2 R_1 R_2}$$

are found from the relations,

$$\alpha + \beta = - \left[\frac{1}{C_1 R_1} + \frac{1}{C_2 R_2} + \frac{1}{C_2 R_1} \right]$$

$$\alpha \beta = \frac{1}{C_1 C_2 R_1 R_2}$$

Taking inverse transform of $v_0(s)$ gives

$$v_0(t) = \frac{V}{R_1 C_2 (\alpha - \beta)} [\exp(-\alpha t) - \exp(-\beta t)]$$

Usually, $\frac{1}{C_1 R_1}$ and $\frac{1}{C_2 R_2}$ will be much smaller compared to $\frac{1}{R_1 C_2}$.

Hence, the roots may be approximated as

$$\alpha \approx \frac{1}{R_1 C_2} \text{ and } \beta = \frac{1}{R_2 C_1}$$

Following a similar analysis, it may be shown that the output waveform for the circuit configuration of Fig. c will be

$$v_0(t) = \frac{V C_1 R_2 \alpha \beta}{(\beta - \alpha)} [\exp(-\alpha t) - \exp(-\beta t)]$$

Multistage Impulse Generators—Marx Circuit

10. Explain the Marx circuit arrangement for multistage impulse generators. How is the basic arrangements modified to accommodate the wave time control resistances? (May'11)

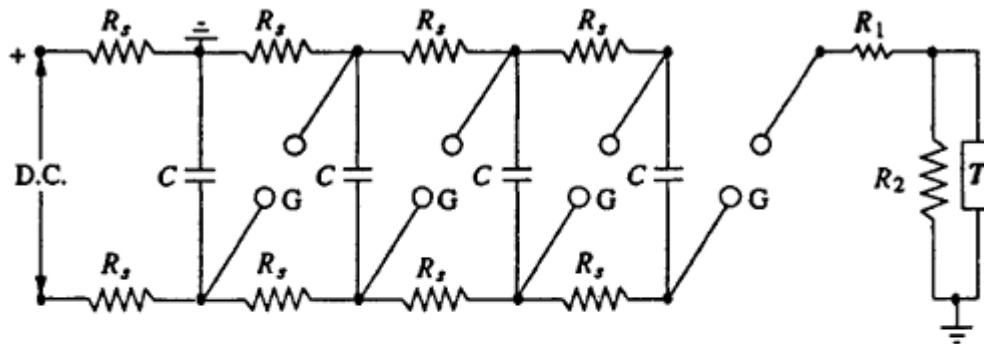


Fig. a Schematic diagram of Marx circuit arrangement for multistage impulse generator

- C — Capacitance of the generator
- R_s — Charging resistors
- G — Spark gap
- R_1, R_2 — Wave shaping resistors
- T — Test object

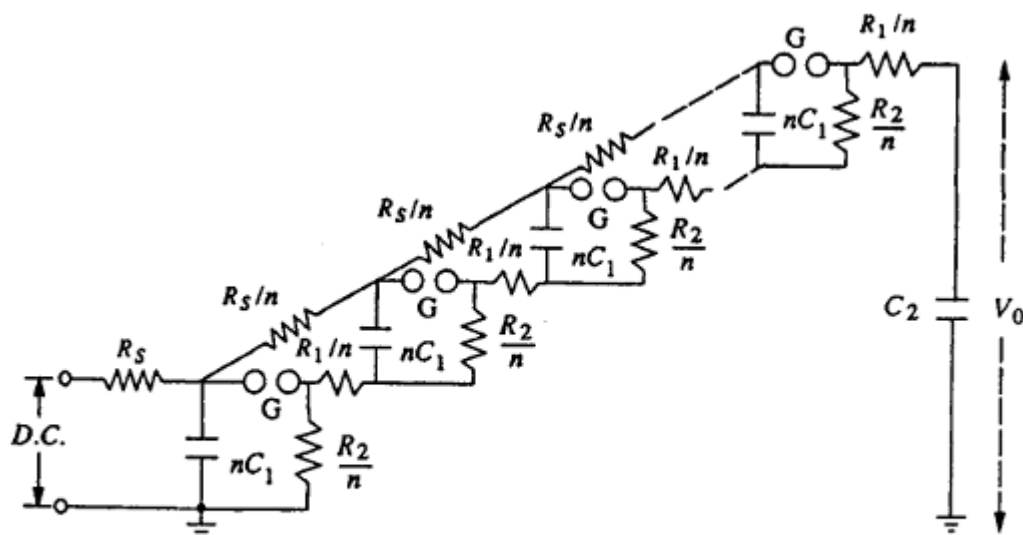


Fig. b Multistage impulse generator incorporating the series and wave tail resistances within the generator

The gap spacing is chosen such that the breakdown voltage of the gap G is greater than the charging voltage V . Thus, all the capacitances are charged to the voltage V in about 1

minute. When the impulse generator is to be discharged, the gaps G are made to spark over simultaneously by some external means. Thus, all the capacitors C get connected in series and discharge into the load capacitance or the test object. The discharge time constant CR_1/n (for n stages) will be very very small (microseconds), compared to the charging time constant CR_s , which will be few seconds. Hence, no discharge takes place through the charging resistors R_s . In the Marx circuit is of Fig. a the impulse wave shaping circuit is connected externally to the capacitor unit In Fig. b, the modified Marx circuit is shown, wherein the resistances R_1 and R_2 are incorporated inside the unit. R_1 is divided into n parts equal to R_1/n and put in series with the gap G . R_2 is also divided into n parts and arranged across each capacitor unit after the gap G . This arrangement saves space, and also the cost is reduced.

Components of a Multistage Impulse Generator

A multistage impulse generator requires several components parts for flexibility and for the production of the required waveshape. These may be grouped as follows:

(i) d.c. Charging Set

The charging unit should be capable of giving a variable d.c. voltage of either polarity to charge the generator capacitors to the required value.

(ii) Charging Resistors

These will be non-inductive high value resistors of about 10 to 100 kilo-ohms. Each resistor will be designed to have a maximum voltage between 50 and 100 kV.

(iii) Generator Capacitors and Spark Gaps

These are arranged vertically one over the other with all the spark gaps aligned. The capacitors are designed for several charging and discharging operations. On dead short circuit, the capacitors will be capable of giving 10 kA of current. The spark gaps will be usually spheres or hemispheres of 10 to 25 cm diameter. Sometimes spherical ended cylinders with a central support may also be used.

(iv) Wave-shaping Resistors and Capacitors

Resistors will be non-inductive wound type and should be capable of discharging impulse currents of 1000 A or more. Each resistor will be designed for a maximum voltage of 50 to 100 kV. The resistances are bifilar wound or non-inductive thin flat insulating sheets. In some cases, they are wound on thin cylindrical formers and are completely enclosed. The load capacitor may be of compressed gas or oil filled with a capacitance of 1 to 10 μF .

(v) Triggering System

This consists of trigger spark gaps to cause spark breakdown of the gaps.

(vi) Voltage Dividers

Voltage dividers of either damped capacitor or resistor type and an oscilloscope with recording arrangement are provided for measurement of the voltages across the test object. Sometimes a sphere gap is also provided for calibration purposes

Generation of Switching Surges

In extra high voltage transmission lines and power systems, switching surge is an important factor that affects the design of insulation. All transmission lines rated for 220 kV and above, incorporate switching surge sparkover voltage for their insulation levels. A switching surge is a short duration transient voltage produced in the system due to a sudden opening or closing of a switch or circuit breaker or due to an arcing at a fault in the system. The waveform is not unique. The transient voltage may be an oscillatory wave or a damped oscillatory wave of frequency ranging from few hundred hertz to few kilo hertz. It may also be considered as a slow rising impulse having a wave front time of 0.1 to 10 ms, and a tail time of one to several ms. Thus, switching surges contain larger energy than the lightning impulse voltages.

Standard switching impulse voltage is defined, as 250/2500 μ S wave, with the same tolerances for time-to-front and time-to-tail as those for the lightning impulse voltage wave i.e. time-to-front of (250 ± 50) μ s and time-to-half value of (2500 ± 500) μ s.

Figure shows the impulse generator circuits modified to give switching surges. The arrangement is the same as that of an impulse generator. Thus, R_1 is about 20 to 30% of R_2 . The efficiency of the generator gets considerably reduced to about 50% or even less. Moreover, the values of the charging resistors R_1 are to be increased to very high values as these will come in parallel with R_2 in the discharge circuit.

The circuit given in Fig. b produces unidirectional damped oscillations. With the use of an inductor L, the value of R_1 is considerably reduced, and the efficiency of the generator increases. The damped oscillations may have a frequency of 1 to 10 kHz depending on the circuit parameters. A sphere gap was included in parallel with the test object for voltage measurement and also for producing chopped waves.

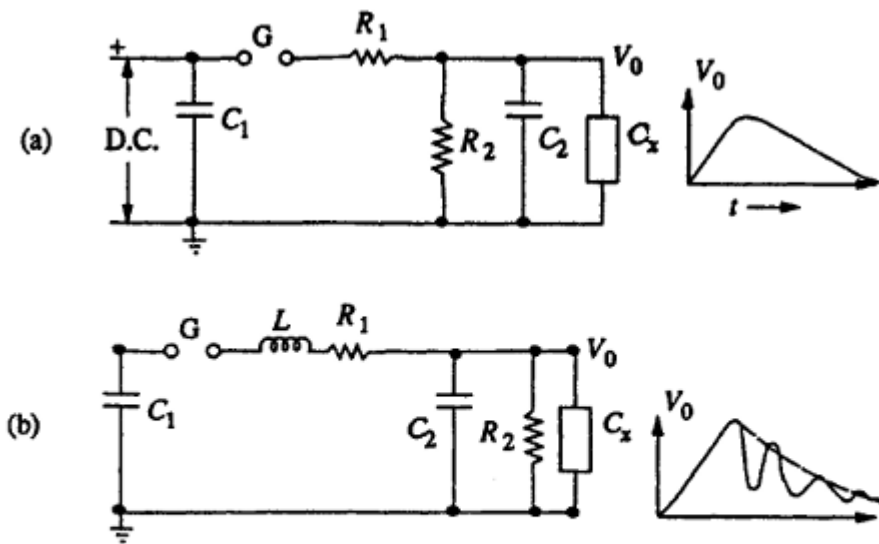


Fig. Circuits for producing switching surge voltages. Also shown are the output waveshapes across the load C_x

Switching surges of very high peaks and long duration can be obtained by using the circuit shown in Fig.. An impulse generator condenser C_1 charged to a low voltage d.c. (20 to 25 kV) is discharged into the low voltage winding of a power or testing transformer. The high voltage winding is connected in parallel to a load capacitance C_2 a potential divider R_1 a sphere gap S , and the test object. Through an autotransformer action, switching surge of proper waveshape can be generated across the test object. The efficiency obtained by this method is high but the transformer should be capable of withstanding very high voltages.

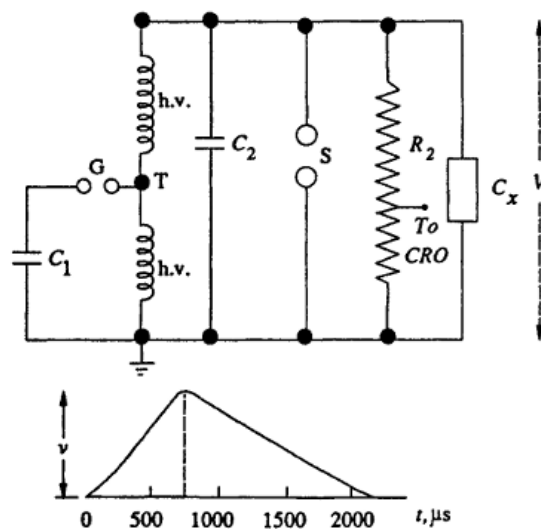


Fig. Circuit for producing switching surges using a transformer

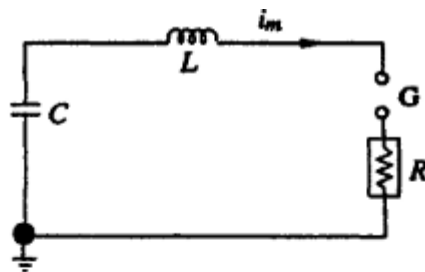
C_1 — Surge generator
 T — Power transformer
 C_2 — Load capacitance
 C_x — Test object

G — Triggering spark gap
 S — Sphere gap
 R_2 — Potential divider
 h.v., l.v. — Transformer high and low voltage windings

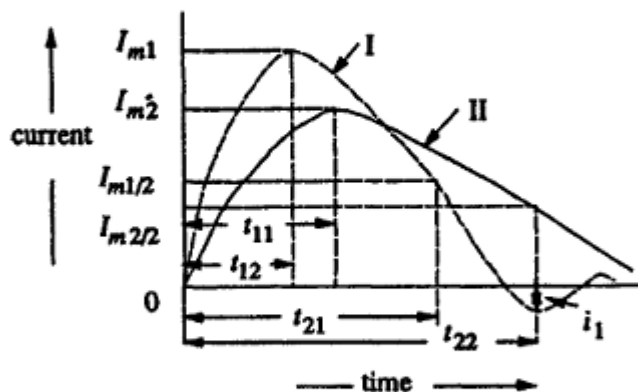
Generation of impulse currents

11. How the impulse current is generated using capacitor bank. Explain in detail. (Dec'11)

Lightening discharges involve both high voltage impulses and high current impulses on transmission lines. Protective gear like surge diverters have to discharge the lightning currents without damage. Therefore, generation of impulse current waveforms of high magnitude find application in testing work as well as in basic research on non-linear resistors, electric arc studies, and studies relating to electric plasmas in high current discharges.



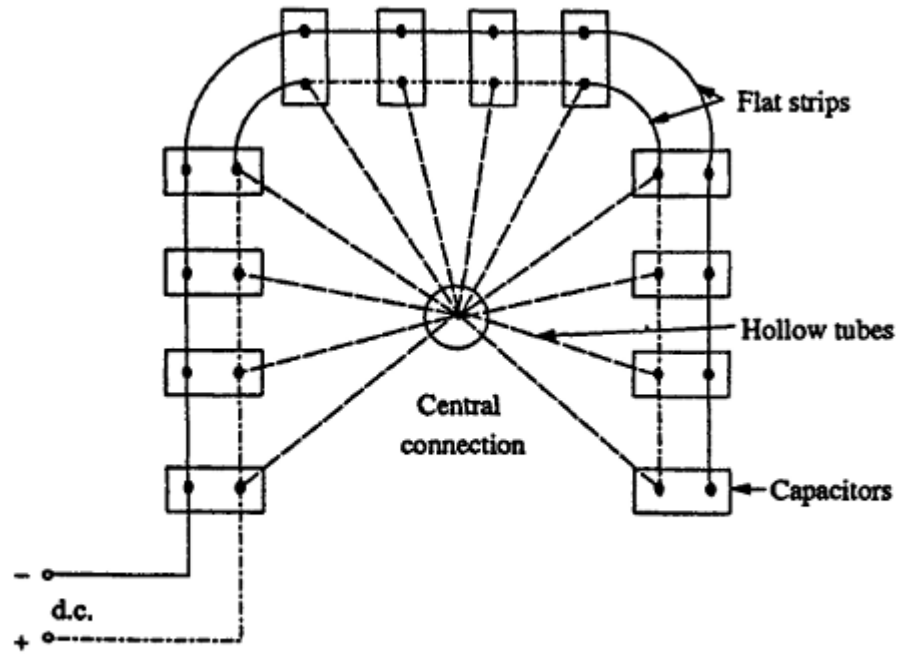
(a) Basic circuit of an impulse current generator



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

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

(b) Types of impulse current waveforms



(c) Arrangement of capacitors for high impulse current generation
Fig. Impulse current generator circuit and its waveform

For producing impulse currents of large value, a bank of capacitors connected in parallel are charged to a specified value and are discharged through a series R - L circuit as shown in Fig. C represents a bank of capacitors connected in parallel which are charged from a d.c. source to a voltage up to 200 kV. R represents the dynamic resistance of the test object and the resistance of the circuit and the shunt L is an air cored high current inductor, usually a spiral tube of a few turns.

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

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

The circuit is usually underdamped, so that

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

Hence, i_m is given by

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

where

$$\alpha = \frac{R}{2L} \text{ and } \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

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

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

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

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

Generation of High Impulse Currents

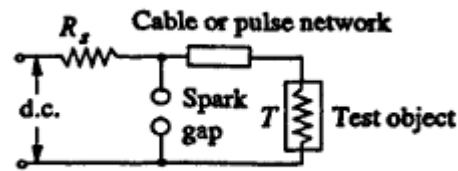
12. Draw a typical impulse current generator circuit and explain its operation and application.

(Dec'19) (May'11)

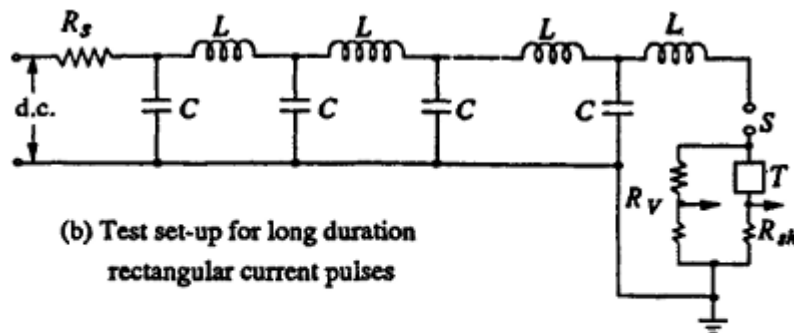
For producing large values of impulse currents, a number of capacitors are charged in parallel and discharged in parallel into the circuit. The arrangement of capacitors is shown in Fig c. In order to minimize the effective inductance, the capacitors are subdivided into smaller units. Also, the arrangement of capacitors into a horse-shoe shaped layout minimizes the effective load inductance.

The essential parts of an impulse current generator are:

- (i) a d.c. charging unit giving a variable voltage to the capacitor bank,
- (ii) capacitors of high value (0.5 to 5 μF) each with very low self-inductance, capable of giving high short circuit currents,
- (iii) an additional air cored inductor of high current value,
- (iv) proper shunts and oscillograph for measurement purposes, and
- (v) a triggering unit and spark gap for the initiation of the current generator.



(a) Basic circuit



(b) Test set-up for long duration rectangular current pulses

Fig. Basic circuit and schematic set-up for producing rectangular current pulses

- R_s — Charging resistor
- S — Trigger spark gap
- T — Test object
- $L-C$ — Pulse forming network
- R_v — Potential divider for voltage measurement
- R_{sh} — Current shunt for current measurement

Triggering and control of impulse generators

13. Explain tripping and control of impulse generators with Trigatron gap arrangements.

(Dec'12) (Dec'13)

In large impulse generators, the spark gaps are generally sphere gaps or gaps formed by hemispherical electrodes. The gaps are arranged such that sparking of one gap results in automatic sparking of other gaps as overvoltage is impressed on the other. In order to have consistency in sparking, irradiation from an ultra-violet lamp is provided from the bottom to all the gaps.

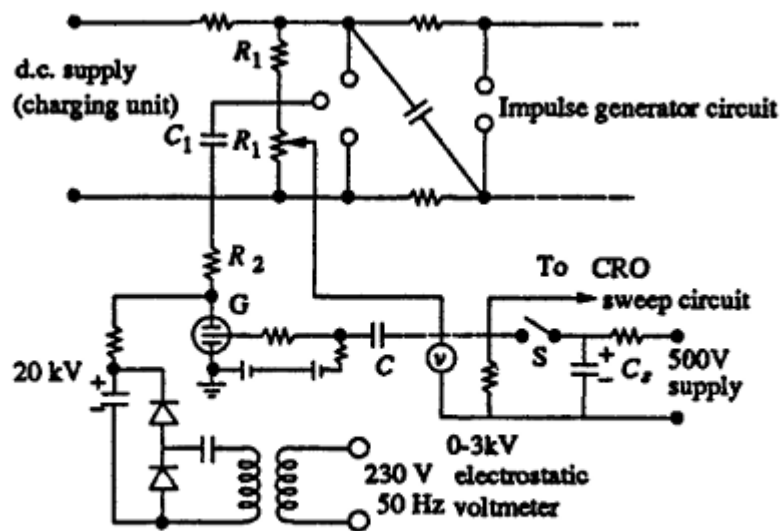


Fig. Tripping of an impulse generator with a three electrode gap

A simple method of controlled tripping consists of making the first gap a three electrode gap and firing it from a controlled source. Figure gives the schematic arrangement of a three electrode gap. The first stage of the impulse generator is fitted with a three electrode gap, and the central electrode is maintained at a potential in between that of the top and the bottom electrodes with the resistors R_1 and R_L . The tripping is initiated by applying a pulse to the thyatron G by closing the switch S. The capacitor C produces an exponentially decaying pulse of positive polarity. The pulse goes and initiates the oscillograph time base. The thyatron conducts on receiving the pulse from the switch S and produces a negative pulse through the capacitance C_1 at the central electrode of the three electrode gap. Hence, the voltage between the central electrode and the top electrode of the three electrode gap goes above its sparking potential and thus the gap conducts.

The three electrode gap requires larger space and an elaborate construction. Now-a-days a trigatron gap shown in Fig. is used, and this requires much smaller voltage for operation compared to the three electrode gap. A trigatron gap consists of a high voltage spherical electrode of suitable size, an earthed main electrode of spherical shape, and a trigger electrode through the main electrode. The trigger electrode is a metal rod with an annular clearance of about 1 mm fitted into the main electrode through a bushing. The trigatron is connected to a pulse circuit as shown in Fig. b. Tripping of the impulse generator is effected by a trip pulse which produces a spark between the trigger electrode and the earthed sphere. Due to space

charge effects and distortion of the field in the main gap, sparkover of the main gap occurs. The trigatron gap is polarity sensitive and a proper polarity pulse should be applied for correct operation.

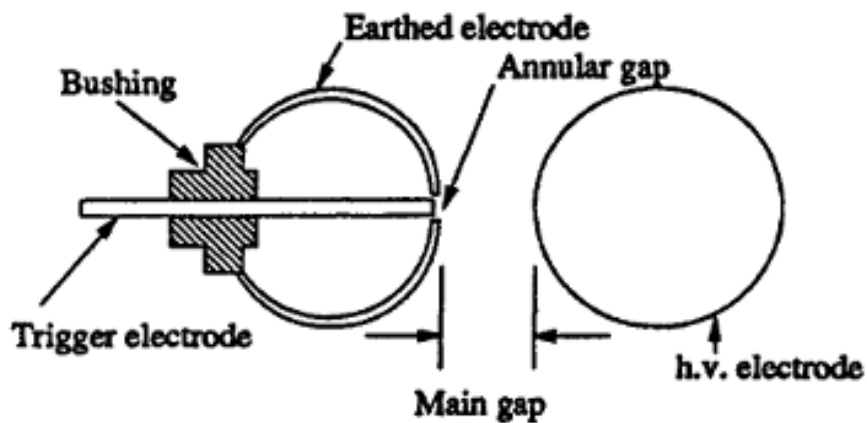
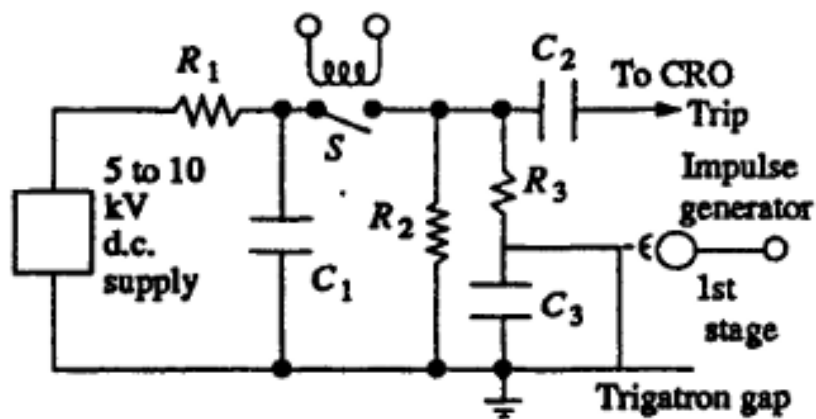


Fig. (a) Trigatron gap



(b) Tripping circuit using a trigatron

Fig. Trigatron gap and tripping circuit

Measurement of High Direct Current Voltages

14. Explain in detail the various techniques for the measurement of high DC voltages.

Measurement of high d.c. voltages as in low voltage measurements, is generally accomplished by extension of meter range with a large series resistance. The net current in the meter is usually limited to one to ten microamperes for full-scale deflection. For very high voltages (1000 kV or more) problems arise due to large power dissipation, leakage currents and limitation of voltage stress per unit length, change in resistance due to temperature variations, etc. Hence, a resistance potential divider with an electrostatic voltmeter is sometimes better when high precision is needed. But potential dividers also suffer from the disadvantages stated above. Both series resistance meters and potential dividers cause current drain from the source.

Generating voltmeters are high impedance devices and do not load the source. They provide complete isolation from the source voltage (high voltage) as they are not directly connected to the high voltage terminal and hence are safer. Spark gaps such as sphere gaps are gas discharge devices and give an accurate measure of the peak voltage. These are quite simple and do not require any specialized construction. But the measurement is affected by the atmospheric conditions like temperature, humidity, etc. and by the vicinity of earthed objects, as the electric field in the gap is affected by the presence of earthed objects. But sphere gap measurement of voltages is independent of the waveform and frequency.

15. Tabulate and explain the methods used for the measurement of high voltages and high currents.

High Voltage Measurement Techniques

Type of voltage	Method or technique
(a) d.c. voltages	(i) Series resistance microammeter (ii) Resistance potential divider (iii) Generating voltmeters (iv) Sphere and other spark gaps
(b) a.c. voltages (power frequency)	(i) Series impedance ammeters (ii) Potential dividers (resistance or capacitance type) (iii) Potential transformers (electromagnetic or CVT)

	(iv) Electrostatic voltmeters (v) Sphere gaps
(c) a.c. high frequency voltages, impulse voltages, and other rapidly changing voltages	(i) Potential dividers with a cathode ray oscillograph (resistive or capacitive dividers) (ii) Peak voltmeters (iii) Sphere gaps

High Current Measurement Techniques

Type of current	Device or technique
(a) Direct currents	(i) Resistive shunts with milliammeter (ii) Hall effect generators (iii) Magnetic links
(b) Alternating currents (Power frequency)	(i) Resistive shunts (ii) Electromagnetic current transformers
(c) High frequency a.c., impulse and rapidly changing currents	(i) Resistive shunts (ii) Magnetic potentiometers or Rogowski coils (iii) Magnetic links (iv) Hall effect generators

High Resistance with series ammeter

(High Ohmic Series Resistance with Microammeter)

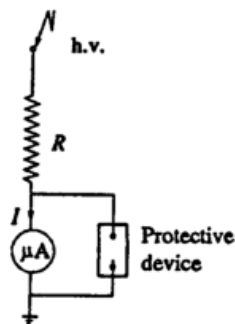


Fig. Series resistance micrometer

High d.c. 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 I

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.

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 d.c. with an accuracy better than 0.2%.

Resistance Potential Dividers for d.c. Voltages

16. Draw a simplified equivalent circuit of resistance potential divider and discuss its

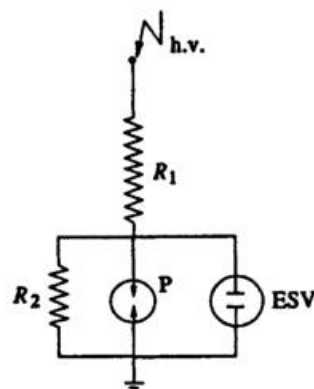


Fig. Resistance potential divider with an electrostatic voltmeter

P — Protective device
ESV — Electrostatic volt-meter

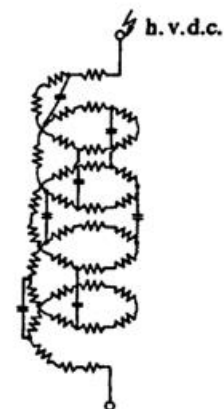


Fig. Series resistor with parallel capacitors for potential linearization for transient voltages

step response.

A resistance potential divider with an electrostatic or high impedance voltmeter is shown in Fig. 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 d.c. 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 these transient voltages, voltage controlling capacitors are connected across the elements. A corona free termination is also necessary 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.

Generating Voltmeters

17. Describe the construction and working of generating voltmeter with necessary sketch.

(Dec'19)

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.

Principle of Operation

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 d.c. voltages $dV/dt = 0$. Hence,

$$i = \frac{dq}{dt} = V \frac{dC}{dt}$$

If the capacitance C varies between the limits C_0 and $(C_0 + C_m)$ sinusoidally as

$$C = C_0 + C_m \sin \omega t$$

the current i is

$$i = i_m \cos \omega t$$

where

$$i_m = V C_m \omega$$

(i_m is the peak value of the current). The rms value of the current is given by:

$$i_{rms} = \frac{VC_m\omega}{\sqrt{2}}$$

For a constant angular frequency ω , 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 a.c. voltage measurements also provided the angular frequency ω is the same or equal to half that of the supply frequency.

Generating voltmeters employ rotating sectors or vanes for variation of capacitance. Figure gives a schematic diagram of a generating voltmeter. 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_3 driven at a constant speed by a synchronous motor at a suitable speed. The rotor vanes of S_0 cause periodic change in capacitance between the insulated disc S_2 and the h.v. 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 a.c. 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.

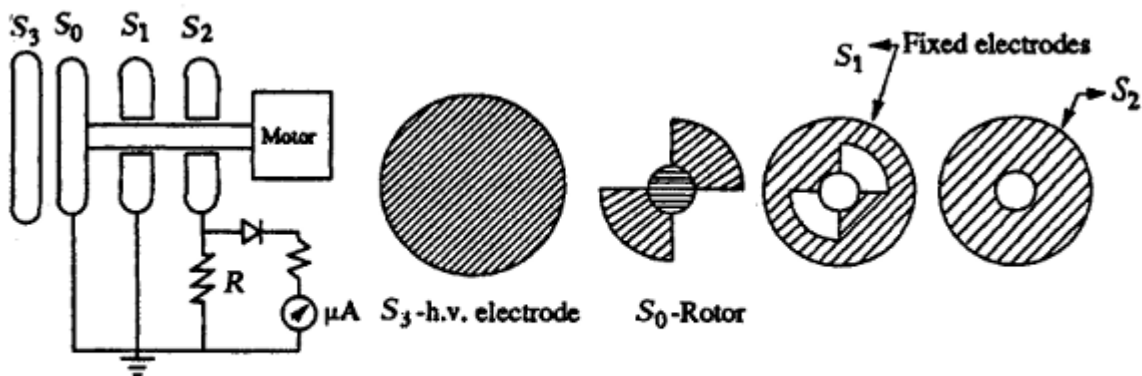


Fig. Schematic diagram of a generating voltmeter (rotating vane type)

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.

MEASUREMENT OF HIGH A.C. AND IMPULSE VOLTAGES:

18. Explain different techniques for measurement of high A.C. and impulse voltages

Series Impedance Voltmeters

For power frequency a.c. 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 Fig. At any frequency ω of the a.c. voltage, the impedance of the resistance R is

$$Z = \frac{R + j\omega L}{(1 - \omega^2 LC) + j\omega CR}$$

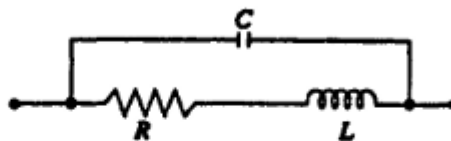


Fig. Simplified lumped parameter equivalent circuit of a high ohmic resistance R

L — Residual inductance

C — Residual capacitance

If ωL and ωC are small compared to R ,

$$Z \approx R \left[1 + j \left(\frac{\omega L}{R} - \omega CR \right) \right]$$

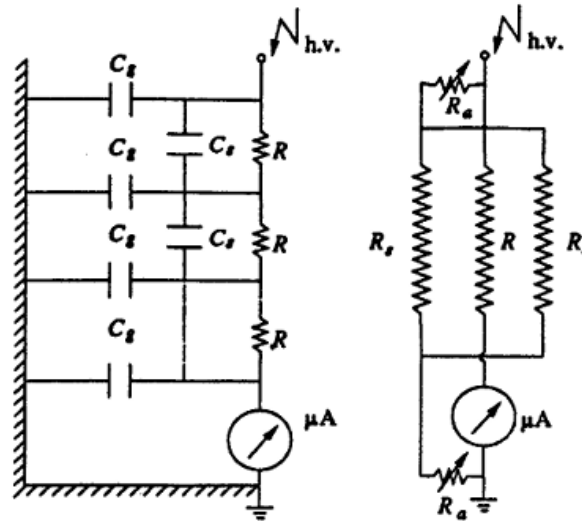
and the total phase angle is

$$\phi \approx \left(\frac{\omega L}{R} - \omega CR \right)$$

This can be made zero and independent of frequency, if

$$L/C = R^2$$

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 tuning resistors is shown in Figs. a and b respectively. Stray ground capacitance effects (refer Fig. b) 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.



(a) Extended series resistance
with inductance neglected

C_g — Stray capacitance to ground
 C_s — Winding capacitance

(b) Series resistance with guard
and tuning resistances

R — Series resistor
 R_s — Guard resistor
 R_a — Tuning resistor

Fig. Extended series resistance for high a.c. voltage measurements

Series Capacitance Voltmeter

To avoid the drawbacks pointed out earlier, a series capacitor is used instead of a resistor for a.c. high voltage measurements. The schematic diagram is shown in Fig. 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 a.c. voltage.

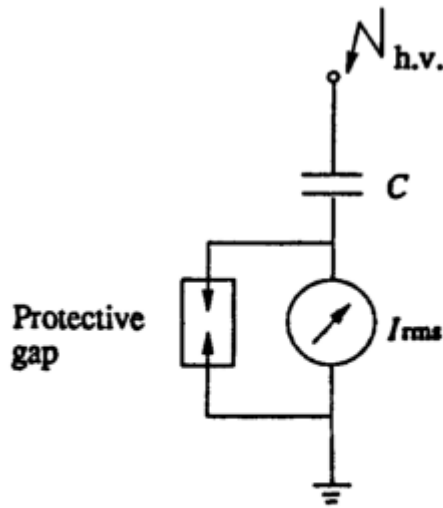


Fig. . Series capacitance with a milliammeter for measurement of high a.c. voltages

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

$$V = \sqrt{V_1^2 + V_2^2 + \dots V_n^2}$$

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

$$I_1 = \omega CV_1$$

$$I_2 = 2 \omega CV_2 \text{ and}$$

$$I_n = n \omega CV_n$$

Hence, the resultant rms current is:

$$I = \omega C (V_1^2 + 4V_2^2 + \dots + n^2 V_n^2)^{1/2}$$

Capacitance Potential Dividers

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.

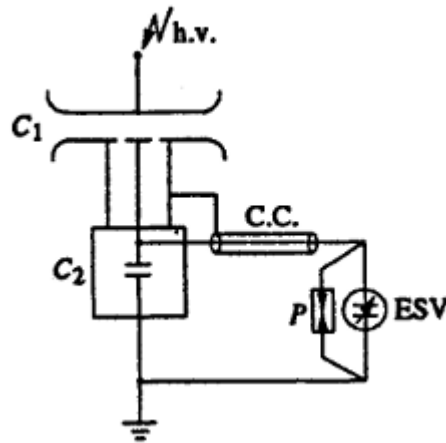


Fig. **Capacitance potential divider**

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

Electrostatic Voltmeters

19. Explain with neat diagram the principle of operation of an Electrostatic Voltmeter. Discuss its advantages and limitations for high voltage measurements. (May'11)

Principle

In electrostatic fields, the attractive force between the electrodes of a parallel plate condenser is given by

$$F = \left| \frac{-\delta W_s}{dS} \right| = \left| \frac{\delta}{\delta S} \left(\frac{1}{2} C V^2 \right) \right| = \left| \frac{1}{2} V^2 \frac{\delta C}{\delta S} \right|$$
$$= \frac{1}{2} \epsilon_0 V^2 \frac{A}{S^2} = \frac{1}{2} \epsilon_0 A \left(\frac{V}{s} \right)^2$$

where, V= applied voltage between plates,

C = capacitance between the plates,

A = area of cross-section of the plates,

s= separation between the plates,

ϵ_0 = permittivity of the medium (air or free space), and

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 millimetre to a few millimetres is usually sufficient for voltage measurements. As the force is proportional to the square of the applied voltage, the measurement can be made for a.c. or d.c. 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 and high insulation resistance. Hence they are considered as devices with high input impedance. The upper frequency limit for a.c. applications is determined from the following considerations:

- (i) natural frequency of the moving system,
- (ii) resonant frequency of the lead and stray inductances with meter capacitance, and

(iii) the R - C behaviour 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 a.c. voltage measurements is better than $\pm 0.25\%$, and for d.c. voltage measurements it may be $\pm 0.1\%$ or less.

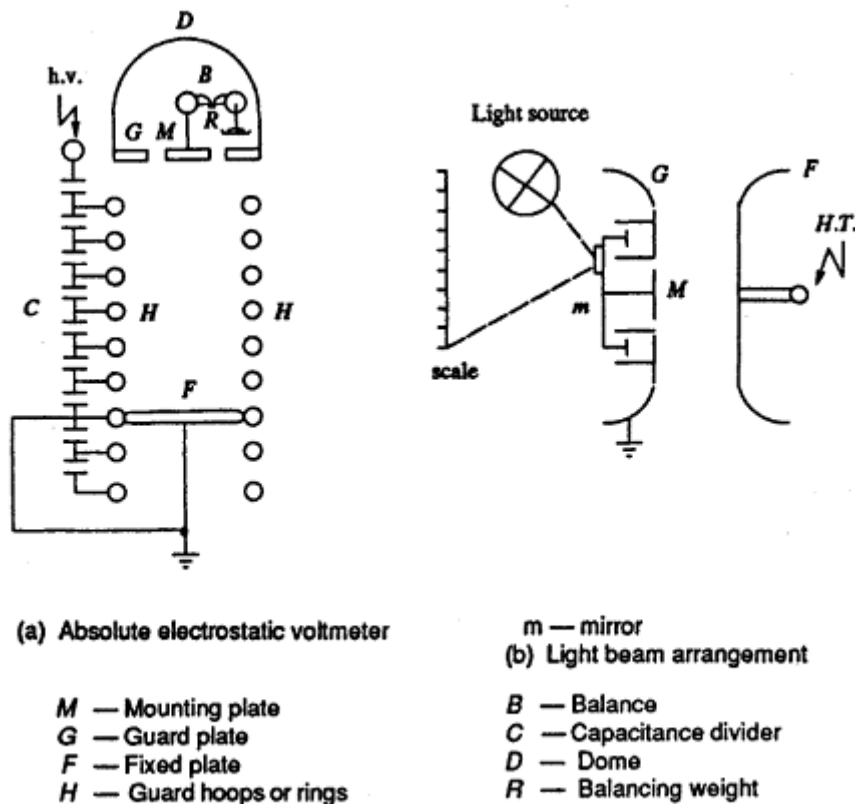


Fig. Electrostatic voltmeter

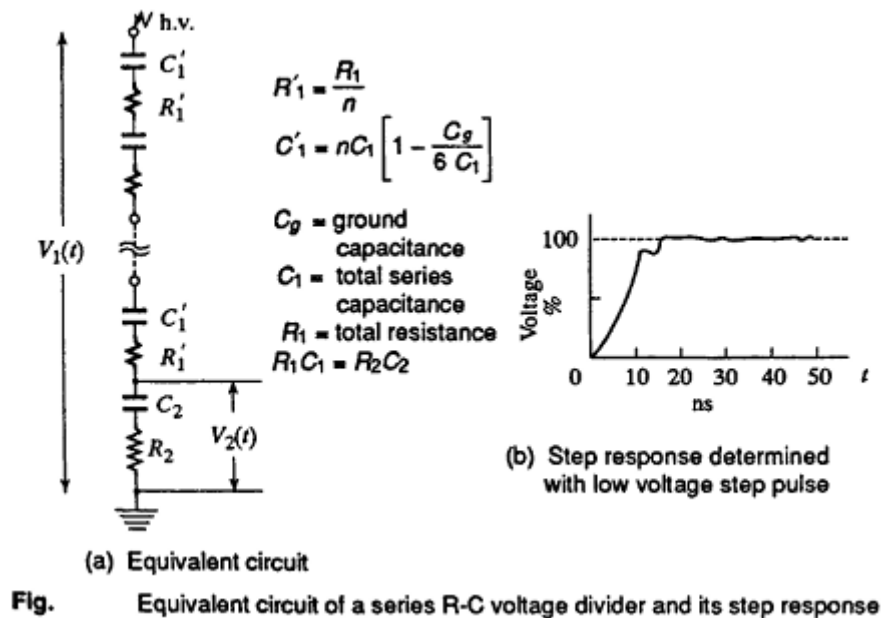
The schematic diagram of an absolute electrostatic voltmeter or electrometer is given in Fig. It consists of parallel plane disc type electrodes separated by a small distance. The moving electrode is surrounded by a fixed guard ring to make the field uniform in the central region. In order to measure 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. The main difference between several forms of voltmeters lies in the manner in which the restoring force is obtained. 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 is 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 W rms and above.

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.

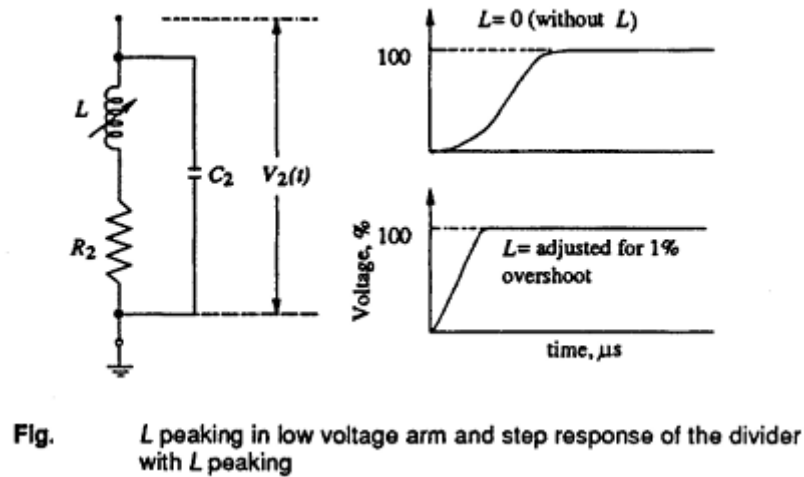
20. Discuss about mixer dividers used for high voltage measurements.

Mixed dividers



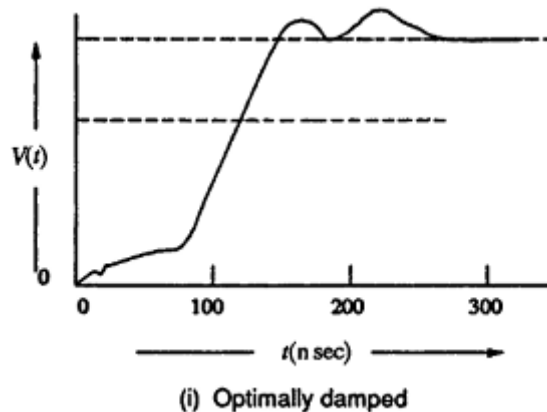
Mixed potential dividers use R - C elements in series or in parallel. One method is to connect capacitance in parallel with each R'_1 element. This is successfully employed for voltage dividers of rating 2 MV and above. A better construction is to make an R - C series element connection. The equivalent circuit of such a construction is shown in Fig. Such dividers are made for 5 MV with response times less than 30 ns. The low voltage arm R_2 is given "L peaking" by connecting

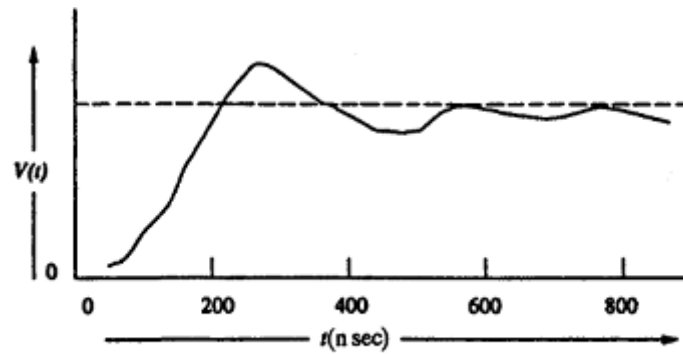
a variable inductance L in series with R_2 . The step response of the divider and the schematic connection of low voltage arm are shown in Fig. However, for a correctly designed voltage divider L peaking will not be necessary.



R-C Potential dividers for 2 MV rating and above

Voltage dividers used for measuring more than one million volts attenuate the measuring signal to a value in the range 100 V to few hundreds of volts. The criteria required to assess the dividers are: (i) the shape of the voltage in the test arrangement should be transferred without any distortion to the L. V. side, (ii) simple determination of transfer behaviour should be ensured, and (iii) they should be suitable for multipurpose use, i.e. for use with a.c. power frequency voltages, switching impulse voltages as well as with lightning impulse voltages. This condition necessitates that the dividers should have broad bandwidths. The above requirements are generally met by (a) optimally damped R-C dividers, or (b) under damped or low damped R-C dividers.

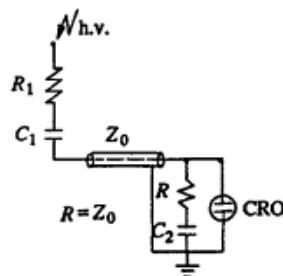




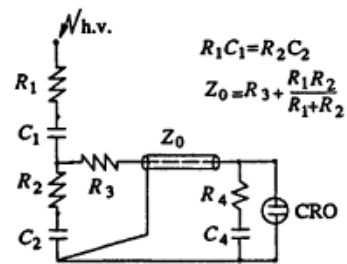
(ii) Underdamped

Fig. Step response of a 4 MV R-C divider

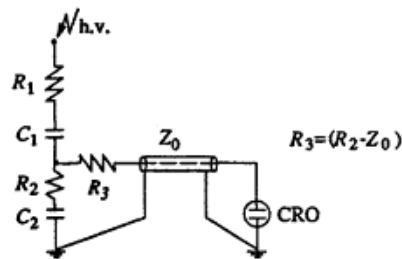
Different arrangements and connections of voltage or potential dividers with a cathode ray oscilloscope are shown in Figs.



(a) R-C series divider



(b) Modified connection of R-C divider



(c) Impedance matching with R-C divider

Fig. Mixed potential divider arrangements

Peak Voltmeter

21. Enumerate digital peak voltmeter.

(Dec'12)

(or)

With neat sketch explain in detail in detail the various methods used to measure the RMS and peak values of high Ac voltages.

(May'15)

In some occasions, the peak value of an a.c. waveform is more important. This is necessary to obtain the maximum dielectric strength of insulating solids, etc. When the waveform is not sinusoidal, rms value of the voltage multiplied by $\sqrt{2}$ is not correct. Hence a separate peak value instrument is desirable in high voltage applications.

Series Capacitor Peak Voltmeter

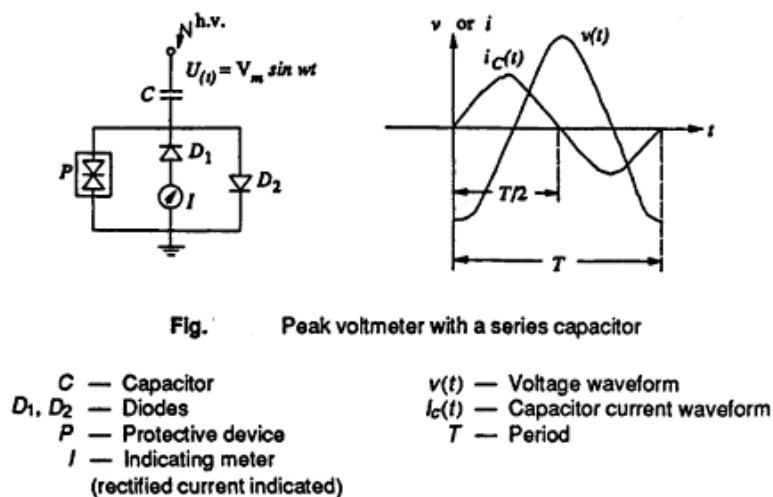
When a capacitor is connected to a sinusoidal voltage source, the charging current $i_0 =$

$$\int_0^t v dt = j\omega CV \text{ where } V \text{ is the rms value of the voltage and } \omega \text{ is the angular frequency. If a half}$$

wave rectifier is used, the arithmetic mean of the rectifier current is proportional to the peak value of the a.c. voltage. The schematic diagram of the circuit arrangement is shown in Fig. The d.c. meter reading is proportional to the peak value of the value V_m or

$$V_m = \frac{I}{2\pi fC}$$

where I is the d.c. current read by the meter and C is the capacitance of the capacitor. This method is known as the Chubb-Froscue method for peak voltage measurement.



The diode D_1 is used to rectify the a.c. current in one half cycle while D_2 by-passes in the other half cycle. This arrangement is suitable only for positive or negative half cycles and hence is valid only when both half cycles are symmetrical and equal. This method is not suitable when the voltage waveform is not sinusoidal but contains more than one peak or maximum as shown in Fig. The charging current through the capacitor changes its polarity within one half cycle itself. The shaded areas in Fig. give the reverse current in any one of the half cycles and the current within that period subtracts from the net current. Hence the reading of the meter will be less and is not proportional to V_m as the current flowing during the intervals $(t_1 - t_2)$ etc will

not be included in the mean value. The second or the false maxima is easily spotted out by observing the waveform of the charging current on an oscilloscope. Under normal conditions with a.c. testing, such waveforms do not occur and as such do not give rise to errors. But pre-discharge currents within the test circuits cause very short duration voltage drops which may introduce errors.

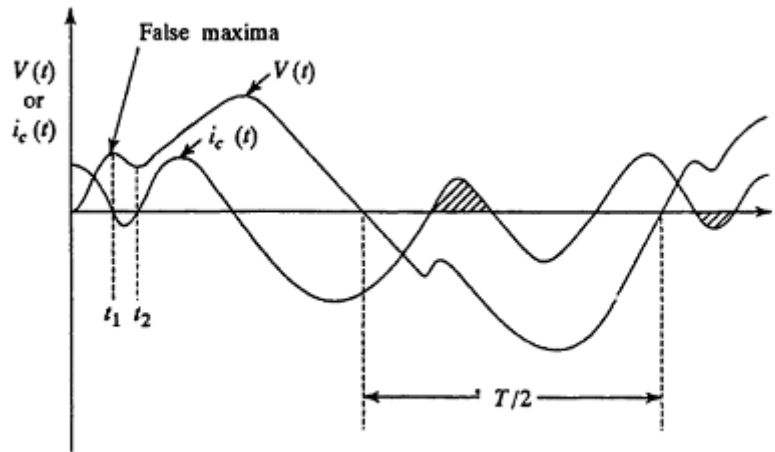


Fig. Voltage waveform with harmonic content showing false maxima

This problem can also be overcome by using a resistance R in series with capacitor C such that $CR \ll 1/\omega$ for 50 Hz application. The error due to the resistance is

$$\frac{\Delta V}{V} = \frac{V - V_m}{V} = \left(1 - \frac{1}{1 + \omega^2 C^2 R^2} \right)$$

where,
 V = actual value, and
 V_m = measured value

In determining the error, the actual value of the angular frequency has to be determined.

The different sources that contribute to the error are

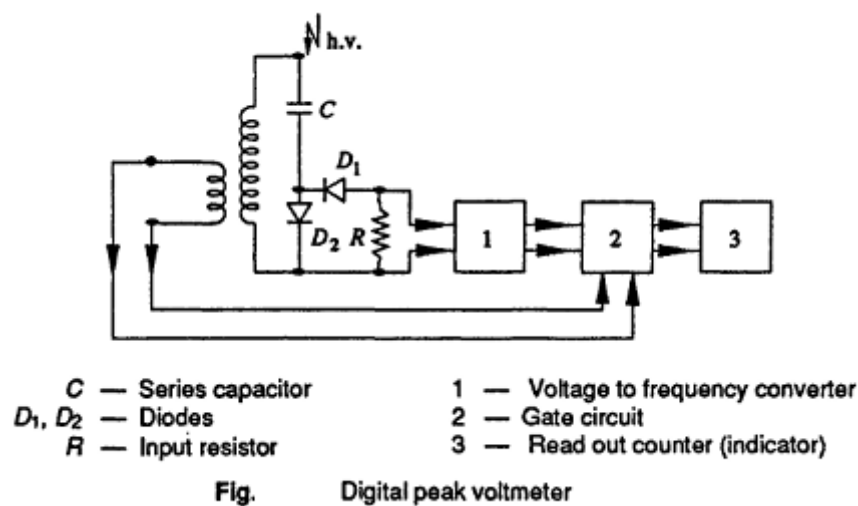
- (i) the effective value of the capacitance being different from the measured value of C
- (ii) imperfect rectifiers which allow small reverse currents
- (iii) non-sinusoidal voltage waveforms with more than one peak or maxima per half cycle
- (iv) deviation of the frequency from that of the value used for calibration

A digital peak reading meter for voltage measurements is shown in Fig. Instead of directly measuring the rectified charging current, a proportional analog voltage signal is derived which is then converted into a proportional medium frequency f_m . The frequency ratio f_m / f is measured with a gate circuit controlled by the a.c. power frequency (f) and a counter that opens

for an adjustable number of periods $\Delta t = p/f$. During this interval, the number of impulses counted, n , is

$$n = f_m \cdot \Delta t = p \cdot \frac{f_m}{f} = 2pCV_m AR$$

where p is a constant of the instrument and A represents the conversion factor of the a.c. to d.c. converter. $A = f_m/(R i_m)$; i_m is the rectified current through resistance R . An immediate reading of the voltage in kV can be obtained by suitable choice of the parameters R and the number of periods p .



Sphere Gaps

22. With neat sketch explain the sphere gap arrangement method of high voltage measurement and give the factors influencing the measurement. (Dec'11), (Dec'13)
(or)

Explain the construction and working of sphere gap with necessary sketch.

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. A sparkover voltage of 30 kV (peak) at 1 cm spacing in air at 20°C and 760 torr pressure occurs for a sphere gap or any uniform field gap. But experience has shown that these measurements are reliable only for certain gap configurations. Normally, only sphere gaps are used for voltage measurements. In certain cases 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 d.c. to impulse voltages of short rise

times (rise time $> 0.5 \mu\text{s}$). As such, sphere gaps can be used for radio frequency a.c. voltage peak measurements also (up to 1 MHz).

Sphere Gap Measurements

Sphere gaps can be 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, it is generally arranged such that both spheres are symmetrically at high voltage above the ground. The two spheres used are identical in size and shape.

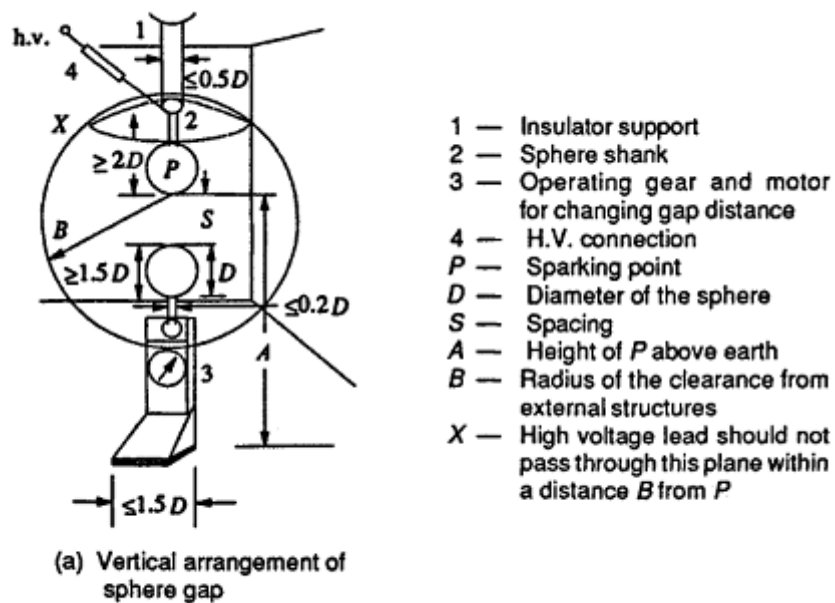


Fig. Sphere gap for voltage measurement

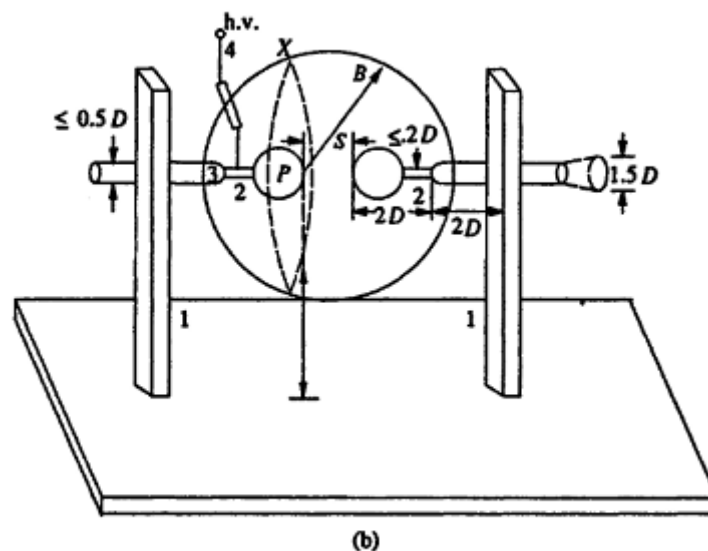


Fig. Horizontal arrangement of sphere gap

The voltage to be measured is applied between the two spheres and the distance or spacing 5 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 kilo ohms for a.c. or d.c. voltages and not more than 500 Ω in the case of impulse voltages.

In the case of a.c. peak value and d.c. 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 $\pm 3\%$.

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.

Sphere Gap Construction and Assembly

Sphere gaps are made with two metal spheres of identical diameters D with their shanks, operating gear, and insulator supports. Spheres are generally made of copper, brass, or aluminium; the latter is used due to low cost. The standard diameters for the spheres are 2, 5, 6.25, 10, 12.5, 15, 25, 50, 75, 100, 150, and 200 cm. The spacing is so designed and chosen such that flashover occurs near the sparking point P . The spheres are carefully designed and fabricated so that their surfaces are smooth and the curvature is uniform. The radius of curvature measured with a spherometer at various points over an area enclosed by a circle of $0.3 D$ around the sparking point should not differ by more than $\pm 2\%$ of the nominal value. The surface of the sphere should be free from dust, grease, or any other coating. The surface should be maintained clean but need not be polished. If excessive pitting occurs due to repeated sparkovers, they should be smoothened.

Factors Influencing the Sparkover Voltage of Sphere Gaps

Various factors that affect the sparkover voltage of a sphere gap are:

- (i) nearby earthed objects,
- (ii) atmospheric conditions and humidity,
- (iii) irradiation, and

(iv) polarity and rise time of voltage waveforms.

(i) Effect of nearby earthed objects

The effect of nearby earthed objects was investigated by Kuffel by enclosing the earthed sphere inside an earthed cylinder. It was observed that the sparkover voltage is reduced. The reduction was observed to be

$$\Delta V = m \log (B/D) + C$$

where,

ΔV = percentage reduction,
 B = diameter of earthed enclosing cylinder,
 D = diameter of the spheres,
 S = spacing, and m and C are constants.

(ii) Effect of atmospheric conditions

The sparkover voltage of a spark gap depends on the air density which varies with the changes in both temperature and pressure. If the sparkover voltage is V under test conditions of temperature T and pressure p torr and if the sparkover voltage is V_0 under standard conditions of temperature $T = 20^\circ\text{C}$ and pressure $p = 760$ torr, then

$$V = kV_0$$

where k is a function of the air density factor d , given by

$$d = \frac{p}{760} \left(\frac{293}{273+T} \right)$$

(iii) Effect of Irradiation

Illumination of sphere gaps with ultra-violet or x-rays aids easy ionization in gaps. The effect of irradiation is pronounced for small gap spacings. A reduction of about 20% in sparkover voltage was observed for spacings of $0.1 D$ to $0.3 D$ for a 1.3 cm sphere gap with d.c. voltages. The reduction in sparkover voltage is less than 5% for gap spacings more than 1 cm, and for gap spacings of 2 cm or more it is about 1.5%. Hence, irradiation is necessary for smaller sphere gaps of gap spacing less than 1 cm for obtaining consistent values.

(iv) Effect of polarity and waveform

It has been observed that the sparkover voltages for positive and negative polarity impulses are different. Experimental investigation showed that for sphere gaps of 6.25 to 25 cm diameter,

the difference between positive and negative d.c. voltages is not more than 1%. For smaller sphere gaps (2 cm diameter and less) the difference was about 8% between negative and positive impulses of 1/50 μ s waveform. Similarly, the wave front and wave tail durations also influence the breakdown voltage. For wave fronts of less than 0.5 μ s and wave tails less than 5 μ s the breakdown voltages are not consistent and hence the use of sphere gap is not recommended for voltage measurement in such cases.

High current shunts

23. Explain any two methods to measure high impulse current.

(Dec'12), (Dec'13)

(or)

Write short notes on high current shunts.

The most common method employed for high impulse current measurements is a low ohmic pure resistive shunt shown in Fig.. The equivalent circuit is shown in Fig. b. The current through the resistive element R produces a voltage drop $v(t)=i(t)R$. The voltage signal generated is transmitted to a CRO through a coaxial cable of surge impedance Z_0 . The cable at the oscilloscope end is terminated by a resistance $R_t= Z_0$ to avoid reflections. The resistance element, because of its large dimensions will have a residual inductance L and a terminal capacitance C . The inductance L may be neglected at low frequencies (ω), but becomes appreciable at higher frequencies (ω) when ωL is of the order of R . Similarly, the value of C has to be considered when the reactance $1/\omega C$ is of comparable value. Normally L and C become significant above a frequency of 1 MHz. The resistance value usually ranges from 10 $\mu\Omega$ to few milliohms, and the voltage drop is usually about a few volts. The value of the resistance is determined by the thermal capacity and heat dissipation of the shunt.

It may be noted here that the stray inductance and capacitance should be made as small as possible for better frequency response of the shunt. The resistance shunt is usually designed in the following manner to reduce the stray effects.

- (a) Bifilar flat strip design,
- (b) coaxial tube or Park's shunt design, and
- (c) coaxial squirrel cage design

(a) Bifilar Strip Shunt

The bifilar design consists of resistor elements wound in opposite directions and folded back, with both ends insulated by a teflon or other high quality insulation. The voltage signal is picked up through a ultra high frequency (UHF) coaxial connector. The shunt suffers from stray inductance associated with the resistance element, and its potential leads are linked to a small part of the magnetic flux generated by the current that is measured. To overcome these problems, coaxial shunts are chosen.

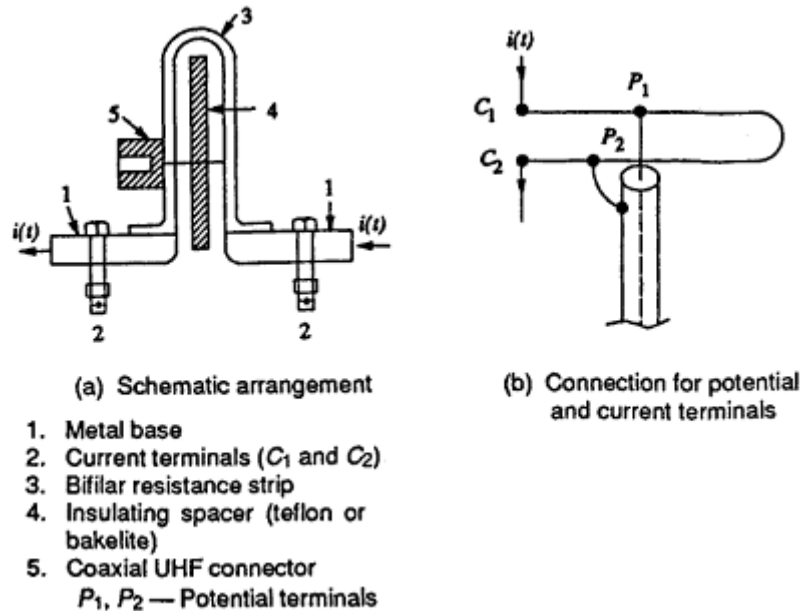


Fig. Bifilar flat strip resistive shunt

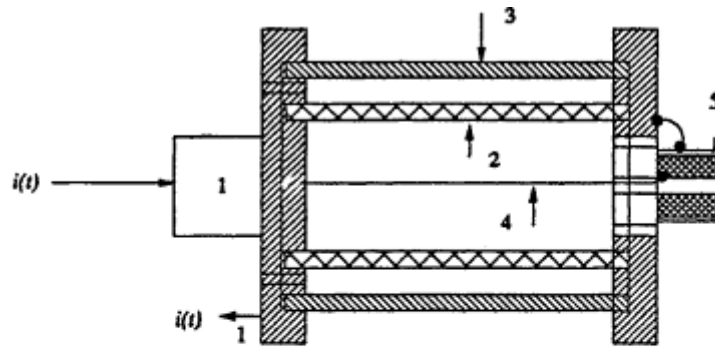
(b) Coaxial Tubular or Park's Shunt

In the coaxial design the current is made to enter through an inner cylinder or resistive element and is made to return through an outer conducting cylinder of copper or brass. The voltage drop across the resistive element is measured between the potential pick-up point and the outer case. The space between the inner and the outer cylinder is air and hence acts like a pure insulator. With this construction, the maximum frequency limit is about 1000 MHz and the response time is a few nanoseconds. The upper frequency limit is governed by the skin effect in the resistive element. The inductance L_Q shown in Fig. may be written as:

$$L_0 = \frac{\mu d l}{2\pi r}$$

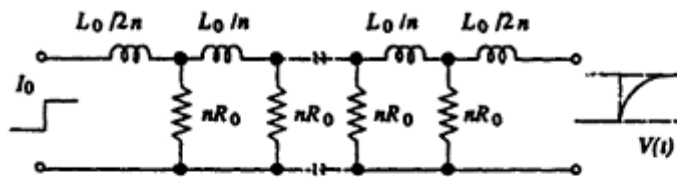
where,

$\mu = \mu_0 \mu_r$; the magnetic permeability, $\mu_0 = 4\pi \times 10^{-9}$ Vs/A cm is the magnetic field constant of vacuum
 $d =$ thickness of the cylindrical tube,

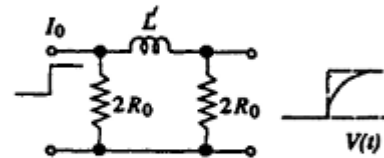


1. Current terminals
2. Coaxial cylindrical resistive element
3. Coaxial cylindrical return conductor (copper or brass tube)
4. Potential pick up lead
5. UHF coaxial connector

Fig. Schematic arrangement of a coaxial ohmic shunt



(a) Exact equivalent circuit

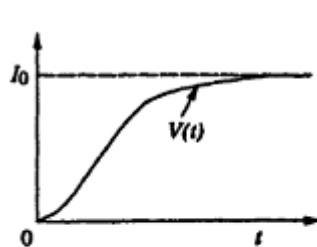


(b) Simplified circuit

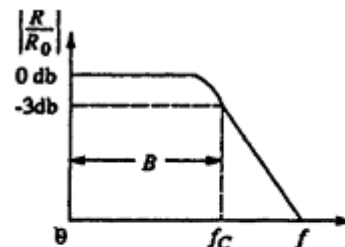
L_0 — Inductance
 R_0 — d.c. resistance
 n — Number of sections per unit length

$$L' = 0.43 L_0$$

Fig. Simplified and exact equivalent circuits of a coaxial tubular shunt



(a) Step response

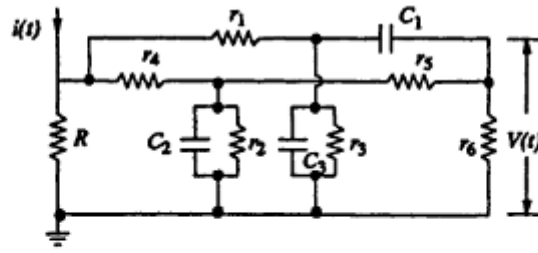


B = Band width
 f_c = Maximum frequency limit.

(b) Frequency response

Fig. Step and frequency responses of a coaxial tubular shunt

(c) Squirrel Cage Shunts



R — Shunt resistance
 $r_1 - r_6$ — Resistors and capacitors in compensating double T network and $C_1 - C_6$

Fig. Compensating network for squirrel cage shunts

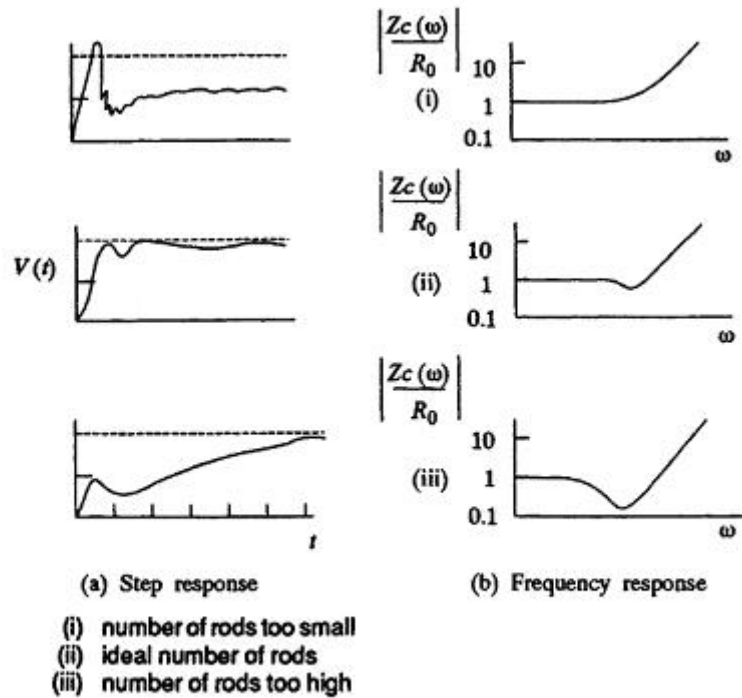


Fig. Response of squirrel cage shunt for different number of rods

In certain applications, such as post arc current measurements, high ohmic value shunts which can dissipate larger energy are required. In such cases tubular shunts are not suitable due to their limitations of heat dissipation, larger wall thickness, and the skin effect. To overcome these problems, the resistive cylinder is replaced by thick rods or strips, and the structure resembles the rotor construction of double squirrel cage induction motor. The equivalent circuit for squirrel cage construction is different, and complex. The shunts show peaky response for step input, and a compensating network has to be designed to get optimum response.

Digital techniques in high voltage measurement

24. Describe the digital techniques used in high voltage measurement.

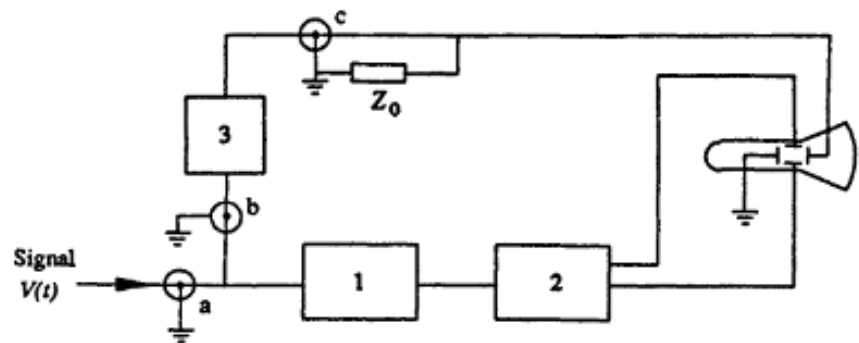
Cathode Ray Oscillographs for Impulse Measurements

Modern oscillographs are sealed tube hot cathode oscilloscopes with photographic arrangement for recording the waveforms. The cathode ray oscilloscope for impulse work normally has input voltage range from 5 m V/cm to about 20 V/cm. In addition, there are probes and attenuators to handle signals up to 600 V (peak to peak). The bandwidth and rise time of the oscilloscope should be adequate. Rise times of 5 n s and bandwidth as high as 500 MHz may be necessary. Sometimes high voltage surge test oscilloscopes do not have vertical amplifier and directly require an input voltage of 10 V. They can take a maximum signal of about 100 V (peak to peak) but require suitable attenuators for large signals. Oscilloscopes are fitted with good cameras for recording purposes.

With rapidly changing signals, it is necessary to initiate or start the oscilloscope time base before the signal reaches the oscilloscope deflecting plates, otherwise a portion of the signal may be missed. Such measurements require an accurate initiation of the horizontal time base and is known as triggering. Oscilloscopes are normally provided with both internal and external triggering facility.

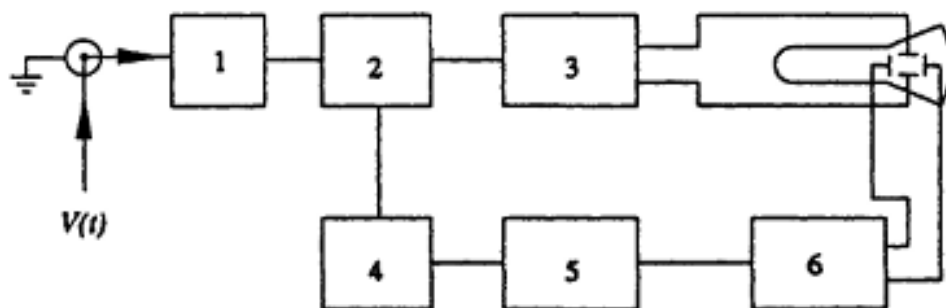
When external triggering is used, as with recording of impulses, the signal is directly fed to actuate the time base and then applied to the vertical or Y deflecting plates through a delay line. The delay is usually 0.1 to 0.5 μ s. The delay is obtained by:

- (1) A long interconnecting coaxial cable 20 to 50 m long. The required triggering is obtained from an antenna whose induced voltage is applied to the external trigger terminal.
- (2) The measuring signal is transmitted to the CRO by a normal coaxial cable. The delay is obtained by an externally connected coaxial long cable to give the necessary delay.
- (3) The impulse generator and the time base of the CRO are triggered from an electronic tripping device. A first pulse from the device starts the CRO time base and after a predetermined time a second pulse triggers the impulse generator.



- | | |
|------------------------|--|
| 1. Trigger amplifier | (a) Vertical amplifier input |
| 2. Sweep generator | (b) Input to delay line |
| 3. External delay line | (c) Output of delay line to CRO Y plates |

Fig. Block diagram of a surge test oscilloscope (older arrangement)



- | | |
|------------------------|----------------------|
| 1. Plug-in amplifier | 4. Trigger amplifier |
| 2. Y amplifier | 5. Sweep generator |
| 3. Internal delay line | 6. X amplifier |

Fig. Simplified block diagram of surge test oscilloscopes (recent schemes)

UNIT IV - HIGH VOLTAGE TESTING & INSULATION COORDINATION

High voltage testing of electrical power apparatus as per International and Indian standards

1. Discuss International and Indian standards for High voltage testing of electrical power apparatus.

Indian standard specifications define 1.2/50 μ s wave to be the standard impulse. The tolerance allowed in the peak value is $\pm 3\%$.

Standard switching impulse voltage is defined, both by the Indian Standards and the IEC, as 250/2500 μ s wave, with the same tolerances for time-to-front and time-to-tail as those for the lightning impulse voltage wave i.e. time-to-front of (250 ± 50) μ s and time-to-half value of (2500 ± 500) μ s. Other switching impulse voltage waves commonly used for testing the lightning arresters are 250/1500 μ s with a tolerance of ± 500 μ s in time-to-half value.

According to the Indian Standard Specifications,

Temperature : 27°C

Pressure : 1013 millibars (or 760 torr)

Absolute humidity : 17 gm/m³

Since it is not always possible to do tests under these reference conditions, corrector factors have to be applied.

In some cases, the following test conditions are also used as reference (British Standard Specifications) conditions.

Temperature : 20°C

Pressure : 1013 millibars (760 Torr)

Absolute humidity : 11 g/m³ (65% relative humidity at 20°C)

Power frequency, impulse voltage and DC testing of Insulators

2. Discuss the various tests to be carried out on an insulator. (May'15) (May'22)

(or)

Explain power frequency, impulse voltage and DC test conducted on insulators.

The tests that are normally conducted are usually subdivided as (i) type tests, and (ii) the routine tests. Type tests are intended to prove or check the design features and the quality. The routine tests are intended to check the quality of the individual test piece. Type tests are done on samples when new designs or design changes are introduced, whereas the routine tests are done

to ensure the reliability of the individual test objects and quality and consistency of the materials used in their manufacture.

High voltage tests include (i) the power frequency tests, and (ii) impulse tests. All the insulators are tested for both categories of test.

Power Frequency Tests

(a) Dry and Wet Flashover Tests In these tests the a.c. voltage of power frequency is applied across the insulator and increased at a uniform rate of about 2 per cent per second of 75% of the estimated test voltage, to such a value that a breakdown occurs along the surface of the insulator. If the test is conducted under normal conditions without any rain or precipitation, it is called "dry flashover test". If the test is done under conditions of rain, it is called "wet flashover test". In general, wet tests are not intended to reproduce the actual operating conditions, but only to provide a criterion based on experience that a satisfactory service operation will be obtained. The test object is subjected to a spray of water of given conductivity by means of nozzles. The spray is arranged such that the water drops fall approximately at an inclination of 45° to the vertical. The test object is sprayed for at least one minute before the voltage application, and the spray is continued during the voltage application.

The characteristics of the spray are

Precipitation rate : $3 \pm 10\%$ (mm/min)

direction : 45° to the vertical

conductivity of water : 100 micro Siemens $\pm 10\%$

water temperature : ambient $\pm 15^\circ\text{C}$

(b) Wet and Dry Withstand Tests (One Minute) In these tests, the voltage specified in the relevant specification is applied under dry or wet conditions for a period of one minute with an insulator mounted as in service conditions. The test piece should withstand the specified voltage.

Impulse Tests

(a) Impulse Withstand Voltage Test This test is done by applying standard impulse voltage of specified value under dry conditions with both positive and negative polarities of the wave. If five consecutive waves do not cause a flashover or puncture, the insulator is deemed to have passed the test. If two applications cause flashover, the object is deemed to have failed. If there is only one failure, additional ten applications of the voltage wave are made. If the test object has withstood the subsequent applications, it is said to have passed the test.

(b) Impulse Flashover Test The test is done as above with the specified voltage. Usually, the probability of failure is determined for 40% and 60% failure values or 20% and 80% failure

values, since it is difficult to adjust the test voltage for the exact 50% flashover values. The average value of the upper and the lower limits is taken. The insulator surface should not be damaged by these tests, but slight marking on its surface or chipping off of the cement is allowed.

(c) *Pollution Testing* Because of the problem of pollution of outdoor electrical insulation and consequent problems of the maintenance of electrical power systems, pollution testing is gaining importance. The normal types of pollution are (i) dust, micro-organisms, bird secretions, flies, etc., (ii) industrial pollution like smoke, petroleum vapours, dust, and other deposits, (iii) coastal pollution in which corrosive and hygroscopic salt layers are deposited on the insulator surfaces, (iv) desert pollution in which sand storms cause deposition of sand and dust layers, (v) ice and fog deposits at high altitudes and in polar countries. These pollutions cause corrosion, non-uniform gradients along the insulator strings and surface of insulators and also cause deterioration of the material. Also, pollution causes partial discharges and radio interference. Hence, pollution testing is important for extra high voltage systems.

Testing of circuit breakers and isolators

3. Describe the various tests to be carried out on a circuit breaker. (Dec'13)

(or)

Explain with a neat diagram of synthetic testing of the circuit breakers. Why are synthetic testing advantages over direct method for short circuit test? (Dec'14)

(or)

Describe the various tests to be carried out on an isolator. (Dec'17)

The testing of isolators and circuit breakers is covered, giving common characteristics for both. While these characteristics are directly relevant to the testing of circuit breakers, they are not much relevant as far as the testing of isolators are concerned since isolators are not used for interrupting high currents. At best, they interrupt small currents of the order of 0.5 A (for rated voltages of 420 k V and below) which may be the capacitive currents of bushings, busbars etc. In fact, the definition of an Isolator or a Disconnecter as per IS: 9921 (Pan I) -1981 is as follows: An isolator or a disconnecter is a mechanical switching device, which provides in the open position, an isolating distance in accordance with special requirements. An isolator is capable of opening and closing a circuit when either negligible current is broken or made or when no significant change in the voltage across the terminals of each of the poles of the isolator occurs.

It is also capable of carrying currents under normal circuit conditions, and carrying for a specified time, currents under abnormal conditions such as those of a short circuit. Thus, most of the discussion here refers to the testing of circuit breakers.

Testing of circuit breakers is intended to evaluate (a) the constructional and operational characteristics, and (b) the electrical characteristics of the circuit which the switch or the breaker has to interrupt or make. The different characteristics of a circuit breaker or a switch may be summarized as per the following groups.

(i) (a) The electrical characteristics which determine the arcing voltage, the current chopping characteristics, the residual current, the rate of decrease of conductance of the arc space and the plasma, and the shunting effects in interruption.

(b) Other physical characteristics including the media in which the arc is extinguished, the pressure developed or impressed at the point of interruption, the speed of the contact travel, the number of breaks, the size of the arcing chamber, and the materials and configuration of the circuit interruption.

(ii) The characteristics of the circuit include the degree of electrical loading, the normally generated or applied voltage, the type of fault in the system which the breaker has to clear, the time of interruption, the time constant, the natural frequency and the power factor of the circuit, the rate of rise of recovery voltage, the restriking voltage, the decrease in the a.c. component of the short circuit current, and the degree of asymmetry and the d.c. component of the short circuit current.

To assess the above factors, the main tests conducted on the circuit breakers and isolator switches are

- (i) the dielectric tests or overvoltage tests,
- (ii) the temperature rise tests,
- (iii) the mechanical tests, and
- (iv) the short circuit tests

Dielectric tests consist of overvoltage withstand tests of power frequency, lightning and switching impulse voltages. Tests are done for both internal and external insulation with the switch or circuit breaker in both the open and closed positions. In the open position, the test voltage levels are 15% higher than the test voltages used when the breaker is in closed position. As such there is always the possibility of line to ground flashover. To avoid this, the circuit breaker is mounted on insulators above the ground, and hence the insulation level of the body of the circuit breaker is raised.

The impulse tests with the lightning impulse wave of standard shape are done in a similar manner as in the case of insulators. In addition, the switching surge tests with switching overvoltages are done on circuit breakers and isolators to assess their performance under overvoltages due to switching operations.

Temperature rise and mechanical tests are tube tests on circuit breakers and are done according to the specifications.

Short Circuit Tests

The most important tests carried out on circuit breakers are short circuit tests, since these tests assess the primary performance of these devices, i.e. their ability to safely interrupt the fault currents. These tests consist of determining the making and breaking capacities at various load currents and rated voltages. In the case of isolators, the short circuit tests are conducted only with the limited purpose to determine their capacity to carry the rated short circuit current for a given duration; and no breaking or making current test is done.

The different methods of conducting short circuit tests are

(I) Direct Tests

- (a) using a short circuit generator as the source
- (b) using the power utility system or network as the source.

(II) Synthetic Tests

(a) Direct Testing in the Networks or in the Fields Circuit breakers are sometimes tested for their ability to make or break the circuit under normal load conditions or under short circuit conditions in the network itself. This is done during period of limited energy consumption or when the electrical energy is diverted to other sections of the network which are not connected to the circuit under test.

The advantages of field tests are:

- * The circuit breaker is tested under actual conditions like those that occur in a given network.
- * Special occasions like breaking of charging currents of long lines, very short line faults, interruption of small inductive currents, etc. can be tested by direct testing only.
- * To assess the thermal and dynamics effects of short circuit currents, to study applications of safety devices, and to revise the performance test procedures, etc.

The disadvantages are:

- * The circuit breaker can be tested at only a given rated voltage and network capacity.
- * The necessity to interrupt the normal services and to test only at light load conditions.
- * Extra inconvenience and expenses in installation of controlling and measuring equipment in the field.

(b) *Direct Testing in Short Circuit Test Laboratories* In order to test the circuit breakers at different voltages and at different short circuit currents, short circuit laboratories are provided. The schematic layout of a short circuit testing laboratory is given in Fig. It consists of a short circuit generator in association with a master circuit breaker, resistors, reactors and measuring devices. A make switch initiates the short circuit and the master circuit breaker isolates the test device from the source at the end of a predetermined time set on a test sequence controller. Also, the master circuit breaker can be tripped if the test device fails to operate properly. Short circuit generators with induction motors as prime movers are also available.

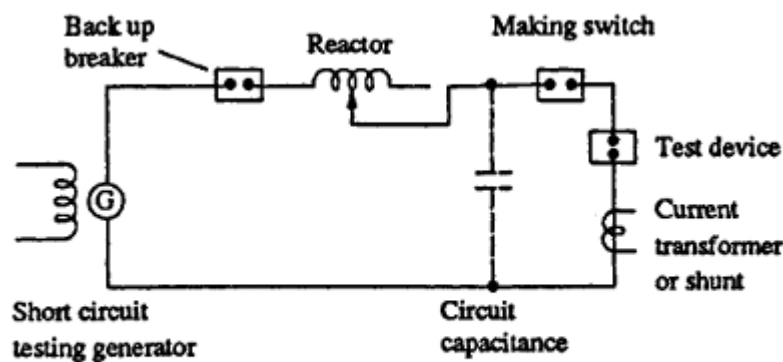
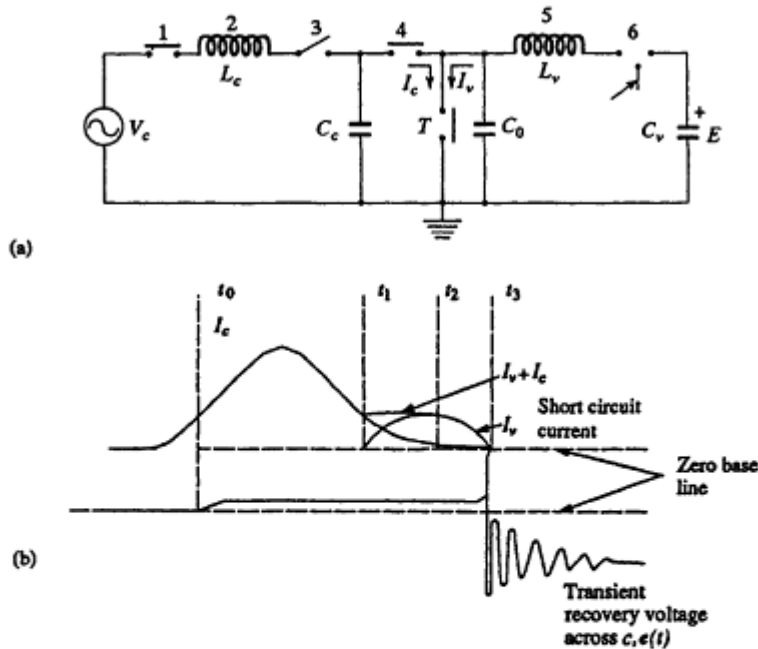


Fig. Schematic diagram showing basic elements of a short circuit testing laboratory

(c) *Synthetic Testing of Circuit Breakers* Due to very high interrupting capacities of circuit breakers, it is not economical to have a single source to provide the required short circuit and the rated voltage. Hence, the effect of a short circuit is obtained as regards to the intensity of the current and the recovery voltage as a combination of the effects of two sources, one of which supplies the a.c. current and the other the high voltage. In the initial period of the short circuit test, the a.c. current source supplies the heavy current at a low voltage, and then the recovery voltage is simulated by a source of comparatively high voltage of small current capacity.

With the auxiliary breaker (3) and the test breaker (T) closed, the closing of the making switch (1) causes the current to flow in the test circuit breaker. At some instant say t_0 , the test circuit breaker (T) begins to operate and the master circuit breaker (1) becomes ready to clear the generator circuit. At some times t_1 , just before the zero of the generator current, the trigger gap (6) closes and the higher frequency current from the discharging capacitor C_v also flows through the arc. At time t_2 , when the generator current is zero, the circuit breaker (1) clears that circuit, leaving only the current from C_v which has the required rate of change of current at its

zero flowing in the test circuit breaker. At the zero of this current/full test voltage will be available. The closing of gap (6) would be a little earlier in time than shown in Fig., but it has been drawn as shown for clarity at current zeros. It is important to see that the high-current source is disconnected and a high-voltage source applied with absolute precision (by means of an auxiliary circuit breaker) at the instant of circuit breaking.



V_c – Low voltage, high current generator; L_c – Current controlling inductance (2); 1 – Master breaker; 3 – Main switch; (T – Circuit breaker) under test; 4 – Auxiliary breaker; (L_v – Voltage waveform) controlling choke (5); 6 – Trigger gap; (C_v – Capacitor charged to) E_v to give necessary recovery voltage; (C_0 – Capacitor to control) the frequency of the transient recovery voltage; t_0 – Opening of auxiliary circuit breaker (4); t_1 – Trigger gap 6 is fired; t_2 – Auxiliary circuit breaker clears and interrupts I_c ; t_3 – I_v becomes zero

Fig. (a) Schematic diagram of synthetic testing of circuit breakers
(b) Current and recovery voltage waveforms across the test circuit breaker

(d) *Composite Testing* In this method, the breaker is first tested for its rated breaking capacity at a reduced voltage and afterwards for rated voltage at a low current. This method does not give a proper estimate of the breaker performance.

(e) *Unit Testing* When large circuit breakers of very high voltage rating (220 k V and above) are to be tested and where more than one break is provided per pole, the breaker is tested for one break at its rated current and the estimated voltage. In actual practice, the conditions of arc in each gap may not be identical and the voltage distribution along several breaks may be uneven. Hence, certain uncertainty prevails in the testing of one break.

(f) *Testing Procedure* The circuit breakers are tested for their (i) breaking capacity B, and (ii) making capacity M. The circuit breaker, after the calibration of the short circuit generator, is tested for the following duty cycle.

- (1) B-3-B-3-B at 10% of the rated symmetrical breaking capacity
- (2) B-3-B-3-B at 30% of the rated symmetrical breaking capacity
- (3) B-3-B-3-B at 60% of the rated symmetrical breaking capacity
- (4) B-3-MB-3MB-MB at 100% breaking capacity with the recovery voltage not less than 95% of the rated service voltage.

The power factor in these tests is generally between 0.15 and 0.3. The numeral 3 in the above duty cycle indicates the time interval in minutes between the tests.

(g) *Asymmetrical Tests* One test cycle is repeated for the asymmetrical breaking capacity in which the d.c. component at the instant of contact separation is not less than 50% of the a.c. component.

Testing of bushing

4. Explain the power frequency and impulse voltage test conducted on bushings. (Dec'11), (Dec'12), (May'15)

(or)

Discuss the various tests to be carried out on a bushing.

Power Frequency Tests

(a) *Power Factor—Voltage Test* In this test, the bushing is set up as in service or immersed in oil. It is connected such that the line conductor goes to the high voltage side and the tank or earth portion goes to the detector side of the high voltage Schering bridge. Voltage is applied up to the line value in increasing steps and then reduced. The capacitance and power factor (or $\tan \delta$) are recorded at each step. The characteristic of power factor or $\tan \delta$ versus applied voltage is drawn. This is a normal routine test but sometimes may be conducted on percentage basis.

(b) *Internal or Partial Discharge Test* This test is intended to find the deterioration or failure due to internal discharges caused in the composite insulation of the bushing. This is done by using internal or partial discharge arrangement. The voltage versus discharge magnitude as well as the quadratic rate gives an excellent record of the performance of the bushing in service. This is now a routine test for high voltage bushings.

(c) *Momentary Withstand Test at Power Frequency* This is done as per the Indian Standard Specifications, IS: 2099, applied to bushings. The test voltage is specified in the specifications.

The bushing has to withstand without flashover or puncture for a minimum time (~ 30 s) to measure the voltage. At present this test is replaced by the impulse withstand test.

(d) One Minute Wet Withstand Test at Power Frequency The most common and routine tests used for all electrical apparatuses are the one minute wet, and dry voltage withstand tests. In wet test, voltage specified is applied to the bushing mounted as in service with the rain arrangement. A properly designed bushing has to withstand the voltage without flashover for one minute. This test really does not give any information for its satisfactory performance in service, while impulse and partial discharge tests give more information.

(e) Visible Discharge Test at Power Frequency This test is intended for determining whether the bushing is likely to give radio interference in service, when the voltage specified in IS: 2099 is applied. No discharge other than that from the arcing horns or grading rings should be visible to the observers in a dark room. The test arrangement is the same as that of the withstand test, but the test is conducted in a dark room.

Impulse Voltage Tests

(a) Full Wave Withstand Test The bushing is tested for either polarity voltages as per the specifications. Five consecutive full waves of standard waveform are applied, and, if two of them cause flashover, the bushing is said to have failed in the test. If only one flashover occurs, ten additional applications are done. The bushing is considered to have passed the test if no flashover occurs in subsequent applications.

(b) Chopped Wave Withstand and Switching Surge Tests The chopped wave test is sometimes done for high voltage bushings (220 kV and 400 kV and above). Switching surge flashover test of specified value is now-a-days included for high voltage bushings. The tests are carried out similar to full wave withstand tests.

Thermal Tests

(a) Temperature Rise and Thermal Stability Tests The purpose of these tests is to ensure that the bushing in service for long does not have an excessive temperature rise and also does not go into the "thermal runaway" condition of the insulation used. Temperature rise test is carried out in free air with an ambient temperature below 40°C at a rated power frequency (50 Hz) a.c. current. The steady temperature rise above the ambient air temperature at any part of the bushing should not exceed 45°C . The test is carried out for such a long time till the temperature is substantially constant, i.e. the increase in temperature rate is less than 1°C/hr . Sometimes, the bushings have to be operated along with transformers, of which the temperature reached may exceed 80°C . This temperature is high enough to produce large dielectric losses and thermal instability. For high voltage bushings this is particularly important, and hence the thermal

stability test is done for bushings rated for 132 kV and above. The test is carried out with the bushing immersed in oil at a maximum temperature as in service, and the voltage applied is 86% of the nominal system voltage. This is approximately $\sqrt{2}$ times the working voltage of the bushing and hence the dielectric losses are about double the normal value. The additional losses account for the conductor ohmic losses. It has been considered unnecessary to specify the thermal stability test for oil-impregnated paper bushings of low ratings; but for the large high voltage bushings the losses in the conductor may be high enough to outweigh the dielectric losses. It may be pointed out here, that the thermal stability tests are type tests. But in the case of large sized high voltage bushings, it may be necessary to make them routine tests.

Testing of transformers

5. Explain the method of impulse testing of high voltage transformers. What is the procedure adopted for locating the failure?

(May'19) (May'11), (May'15)

a) Induced Overvoltage Test

Transformers are tested for overvoltages by exciting the secondary of the transformer from a high frequency a.c. source (100 to 400 Hz) to about twice the rated voltage. This reduces the core saturation and also limits the charging current necessary in large power transformers. The insulation withstand strength can also be checked.

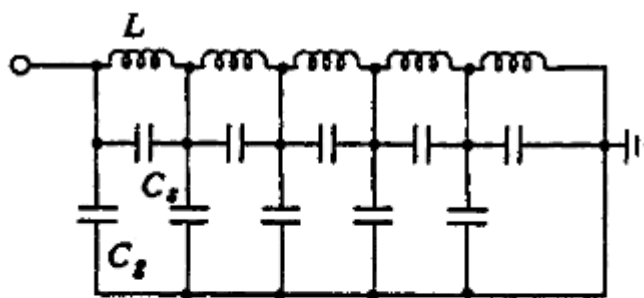
(b) Partial Discharge Tests

Partial discharge tests on the windings are done to assess the discharge magnitudes and the radio interference levels. The transformer is connected in a manner similar to any other equipment and the discharge measurements are made. The location of the fault or void is sometimes done by using the travelling wave technique similar to that for cables. So far, no method has been standardized as to where the discharge is to be measured. Multi-terminal partial discharge measurements are recommended. Under the application of power frequency voltage, the discharge magnitudes greater than 10^4 pico coulomb are considered to be severe, and the transformer insulation should be such that the discharge magnitude will be far below this value.

Impulse Testing of Transformers

The purpose of the impulse tests is to determine the ability of the insulation of the transformers to withstand the transient voltages due to lightning, etc. Since the transients are impulses of short rise time, the voltage distribution along the transformer winding will not be uniform. The equivalent circuit of a transformer winding for impulses is shown in Fig. If an impulse wave

is applied to such a network the voltage distribution along the element will be uneven, and oscillations will be set in producing voltages much higher than the applied voltage. Impulse testing of transformers is done using both the full wave and the chopped wave of the standard impulse, produced by a rod gap with a chopping time of 3 to 6 μ s. To prevent large overvoltages being induced in the windings not under test, they are short circuited and connected to ground. But the short circuiting reduces the impedance of the transformer and hence poses problems in adjusting the standard waveshape of the impulse generators. It also reduces the sensitivity of detection.



L — Inductance (series)
 C_s — Series capacitance
 C_g — Shunt capacitance to ground

Fig. Equivalent circuit of transformer winding for impulses

(a) Procedure for Impulse Testing

The schematic diagram of the transformer connection for impulse testing is shown in Fig. and the wave shapes of the full and chopped waves are shown in Fig. In transformer testing it is essential to record the waveforms of the applied voltage and current through the windings under test. Sometimes, the transferred voltage in the secondary and the neutral current are also recorded. Impulse testing is done in the following sequence:

- (i) applying impulse voltage of magnitude 75% of the Basic Impulse Level (BIL) of the transformer under test,
- (ii) one full wave voltage of 100% BIL,
- (iii) two chopped waves of 100% BIL,
- (iv) one full wave of 100% BIL, and

(v) one full wave of 75% BIL.

It is very important to see that the grounding is proper and the windings not under test are suitably terminated.

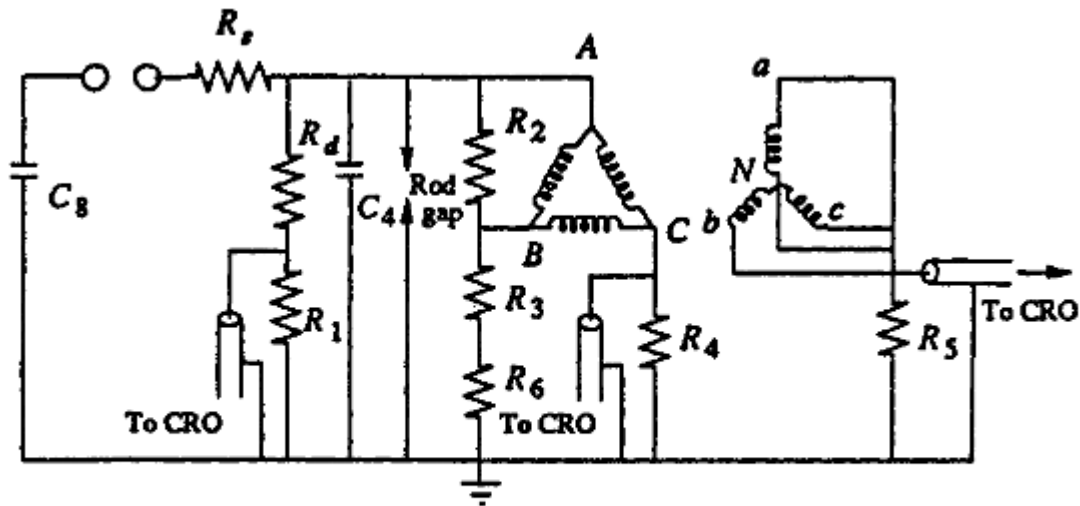


Fig. Arrangement of transformer for impulse testing

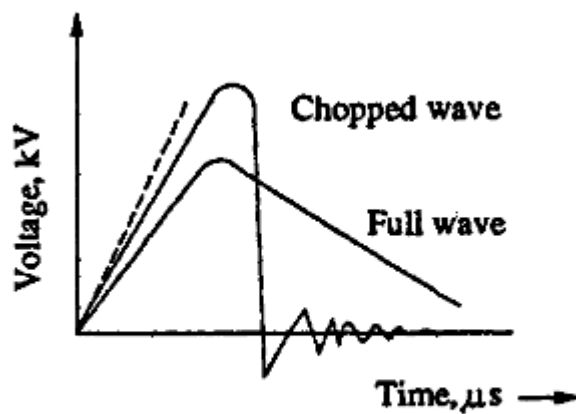


Fig. Full wave and chopped wave

(b) Detection and Location of Fault During Impulse Testing

The fault in a transformer insulation is located in impulse tests by any one of the following methods.

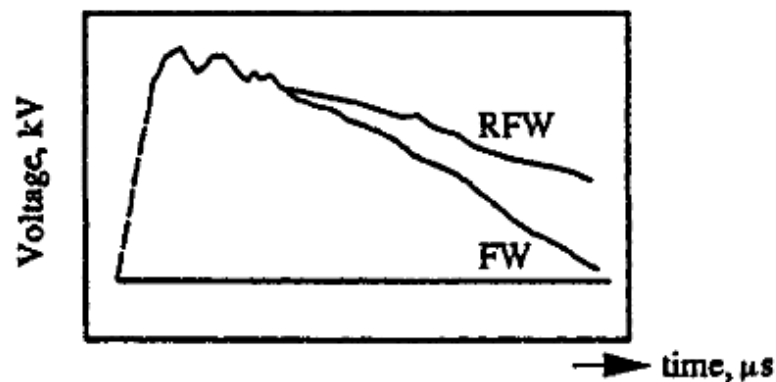
General observations: The fault can be located by general observations like noise in the tank or smoke or bubbles in breather.

Voltage oscillogram method : Fault or failure appears as a partial or complete collapse of the applied voltage wave. Figure gives the typical waveform. The sensitivity of this method is low and does not detect faults which occur on less than 5% of the winding.

Neutral current method : In the neutral current method, a record of the impulse current flowing through a resistive shunt between the neutral and ground point is used for detecting the fault. The neutral current oscillogram consists of a high frequency oscillation, a low frequency disturbance, and a current rise due to reflections from the ground end of the windings. When a fault occurs such as arcing between the turns or from turn to the ground, a train of high frequency pulses similar to that in the front of the impulse current wave are observed in the oscillogram and the wave shape changes. If the fault is local, like a partial discharge, only high frequency oscillations are observed without a change of wave shape. The sensitivity of the method decreases, if other windings not under test are grounded.

Transferred surge current method: In this method, the voltage across a resistive shunt connected between the low voltage winding and the ground is used for fault location. A short high frequency discharge oscillation is capacitively transferred at the event of failure and is recorded. Hence, faults at a further distance from the neutral are also clearly located. The wave shape is distorted depending on the location and type of fault, and hence can be more clearly detected.

After the location of the fault, the type of fault can be observed by dismantling the winding and looking for charred insulation or melted parts on the copper winding. This is successful in the case of major faults. Local faults or partial discharges are self healing and escape observation.



(b) 8.5% of winding failed

Fig. Voltage oscillograms of transformer winding with a fault
RFW—Reduced full wave
FW— Full wave

Insulation Coordination

6. Describe the principles of insulation coordination on high voltage and extra high voltage power systems

(or)

Explain the different aspects of insulation design and insulation co-ordination adopted for EHV systems.

Electric power supply should ensure reliability and continuity to the utility concerns. Hence, the power lines and sub-stations are to be operated and protected against overvoltages such that the number of failures are as few as possible. At the same time, the cost involved in the design, installation, and operation of the protective devices should not be too high. Hence, a gradation of system insulation and protective device operation is to be followed, keeping in view the importance of the various equipment involved.

Generally, sub-stations contain transformers, switchgear, and other valuable equipment with non-self restoring insulation, which have to be protected against failures and internal destruction. For other apparatus, which contain self-restoring insulation, like string insulators, they may be allowed to flashover in air. But the flashovers should be kept to a minimum so that the system disturbances are the least.

Hence, lightning and switching surge protection requires establishment of protective voltage levels called shunt protection levels, by means of protective devices like lightning arresters.

The lightning impulse withstand level known as the Basic Impulse Level (BIL) is established for each system nominal voltage for different apparatus. Various equipment and their component parts should have their BIL above the system protective level, by a suitable margin. This margin is usually determined with respect to air insulation by statistical methods. For non self-restoring insulation like the transformer insulation, the margin limit is fixed using conventional methods.

For system voltages below 400 kV, the switching surges are not of importance. If the BIL is chosen correctly, relative to the prevailing protective level, the equipment will have an adequate switching surge level. For higher system voltages, since the switching surges are of higher magnitude compared to the lightning overvoltages, switching surge magnitudes are of importance and the following criterion is to be adopted.

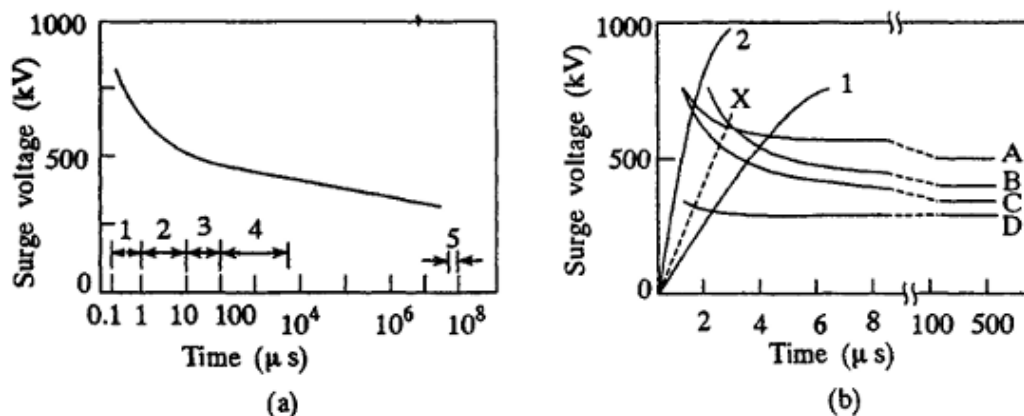
* The flashover voltage of a protective device is chosen such that it will not operate for switching overvoltages and other power frequency and its harmonic overvoltages. But other long duration overvoltages, namely, sustained over voltage due to faults and even the above-

mentioned overvoltages may sometimes cause thermal overloading due to leakage currents. Therefore, the BIL has to be higher.

* For EHV systems, it may be economical to use a protective device for limiting the overvoltages due to lightning as well as switching surges to a particular level. At present, there are surge diverters which operate for both types of overvoltages mentioned above. In such cases, it is preferable to assign to each protected equipment a Switching Impulse Level (SIL), so that there is a small margin above the controlled switching surge level, so that the surge diverters operate on switching surges, only when the controlling devices fail. Normally, only rod gaps and lightning arresters are used as protective devices for protection, and their characteristics are considered here.

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

- (a) It should not usually flashover for power frequency overvoltages.
- (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 agencies, 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.



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

Fig. Volt-time characteristics of transformer rod gaps and surge diverters

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 outage 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.

Insulation Co-ordination in EHV and UHV Systems

The insulation design of EHV and UHV stations is based on the following principles

- * Stations have transformers and other valuable equipment that have non-self restoring insulation, and
- * The protective levels for lightning surges and switching surges are almost equal and even overlap. If the basic impulse level for the equipment or the system is chosen, then this level cannot give protection against the switching impulses. Hence, a separate switching impulse level (SIL) has to be chosen. It is therefore, desirable to use protective devices for limiting both lightning and switching overvoltages. As such, the switching impulse insulation level above the controlled switching surge level has to be adopted so that the surge diverters operate only rarely on switching overvoltages when the controls of the control devices for switching voltages fail.

UNIT V APPLICATION IN INDUSTRY

Electrostatic Precipitation

1. With neat sketch discuss in detail about Electrostatic Precipitation.

Electrostatic precipitation is essentially the charging of dust particles in a gas and their subsequent separation under the effect of the electric field. These processes may occur within a single zone or be distributed over two zones, where the first zone-the charging zone-is intended to charge the particles, and the second zone-the collecting zone-is designed to settle the particles.

The stream of ions charging the dust particles is produced by means of a corona discharge in an inhomogeneous electric field. These ions interact with the particulates entrained in the gas and impart charge to the dust, which then experiences a force towards the collecting electrode where it is held by electrostatic forces until it is removed by mechanical rapping.

Two systems of electrodes are used in electrostatic precipitators to obtain an inhomogeneous electric field: a wire conductor enclosed in a cylindrical pipe (pipe-type precipitators), or a row of wire conductors located between plates (plate- or duct-type precipitators). The electrodes around which a corona discharge is formed are termed the discharge electrodes, whereas the electrodes receiving the charged dust particles, deposited by the action of the electric field, are the collecting electrodes.

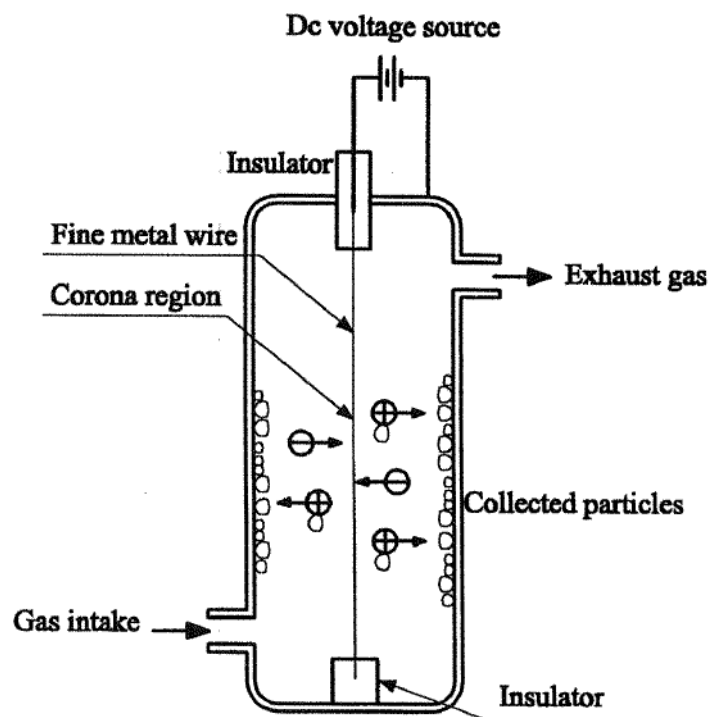


Fig. Pipe-type electrostatic precipitator

Figure displays schematically the charging of dust particles in a precipitator. The particles are charged as a result of bombardment by ions energized in the electric field, for particles larger than 1 μm , and through collision with ions which participate in the continuous thermal motion of molecules without the aid of an electric field, for particles in the sub-micron range.

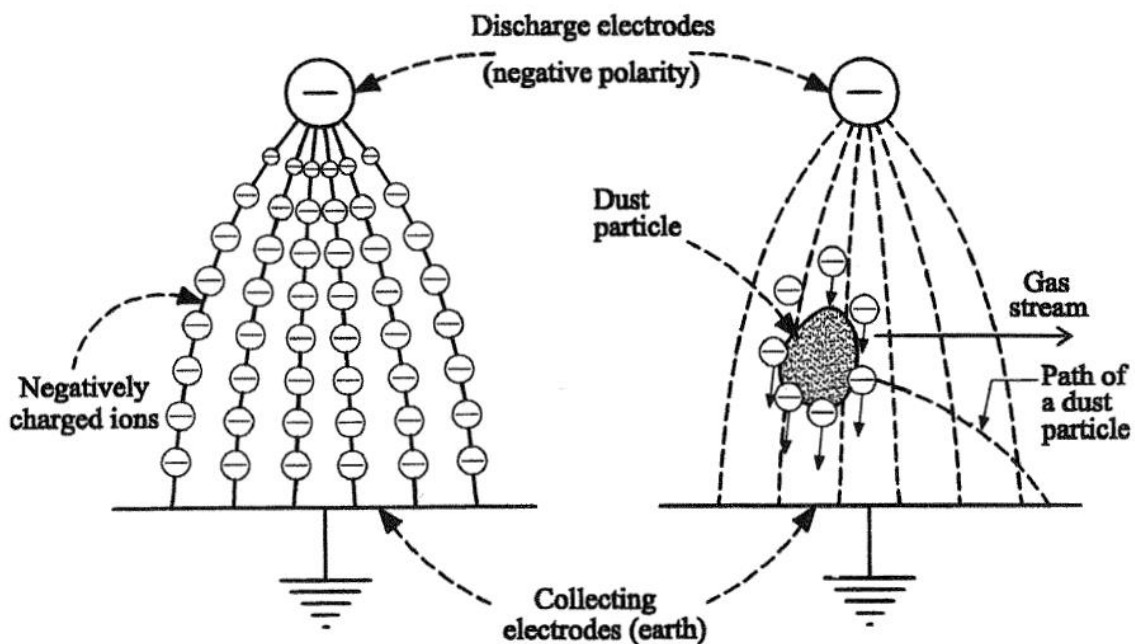


Fig. Schematic diagram illustrating the charging of dust particles in an electrostatic precipitator

A dust cake on a collecting electrode consists of only 10-50% dust, depending on the size of the particles, the remaining part being channels (cracks) filled with gas. Because of a difference in the values of relative permittivities of dust and gas, the lines of electric field concentrate inside the channels. When the voltage is high, an electric breakdown takes place across the dust cake, and the gas inside the channels is ionized. The outlet of each channel acts then as a point discharge on the collecting electrode. This phenomenon is termed back corona.

High resistivity particles cause back corona to be formed in the precipitated layer and this has a number of deleterious effects. The most significant is the release of ions which move countercurrent with respect to the dust particles and partly neutralize their charges, so that dust collection is adversely affected and current intensity in the precipitator greatly increases. This is in addition to a reduction in the sparkover voltage, which consequently reduces the precipitator's performance.

Pulse charging was proposed as an alternative solution to back discharge. A train of pulses, usually superimposed on a DC level value, provides a high peak electric field for particle charging. However, the mean collector current in this case depends not only on the peak voltage

but also on the pulse duty cycle. In this way the voltage and current can be decoupled by changing the mark / space ratio of the applied pulses, and high charging fields can be established without back discharge. Pulse charging can produce a uniform distribution of ionic current on both the discharge and collecting electrodes. The disadvantage of pulse charging is the ion shortage that occurs when the current must be lowered extremely to cope with high dust resistivity. This results in a low charging rate which impairs the performance even if back discharge is avoided.

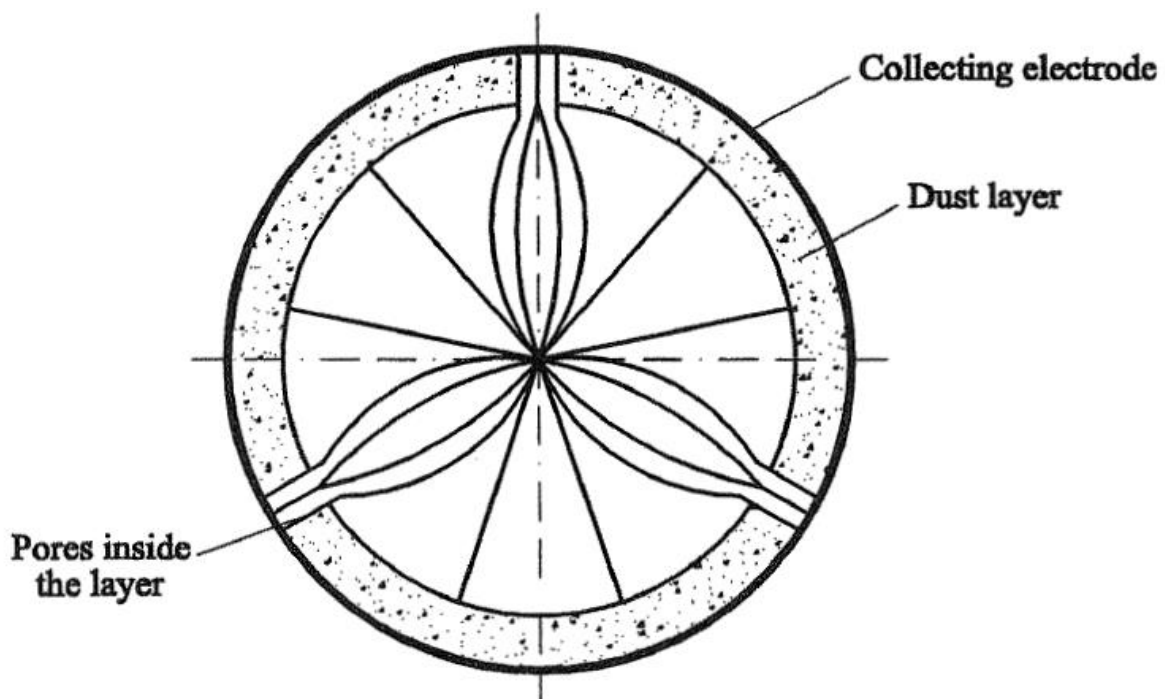


Fig. Schematic diagram illustrating the arrangement of field lines on formation of back corona

To overcome this shortcoming, prechargers have been proposed. The fundamental aim of all precharger systems is to separate the charging and collecting processes into two separate stages. In the charging stage, different techniques are used to eliminate or reduce the effects of back corona, whereas the collecting stage is similar for all prechargers and comprises only parallel plates so that no back corona can be formed. Different types of precharger have been developed and tested at pilot-scale stage, including the trielectrode charger, high-intensity charger, boxer charger, and cold-pipe charger.

Precipitator efficiency can reach or even exceed 99%, depending on several design parameters, including the dimensions and geometry of the gas duct, gas temperature and velocity, average size and resistivity of the particulates, and corona discharge intensity.

Separation

2. Explain the process of Electrostatic Separation.

Electrostatic separation is the selective sorting of solid species by means of utilizing forces acting on these species in an electric field. The main items of the separator are a charging mechanism in the charging zone, an external electric field in the separating zone, and a feeding and product collection system.

The charging of two different species entering the separating zone results in: (a) particles bear electric charges of opposite sign; or (b) only one type of particle bears an electric charge; or (c) particles bear the same sign of charge, but the magnitude of the electric charge is significantly different. Although there are many ways to charge solid particles, the most common mechanisms are as follows.

1. Charging by contact and frictional electrification is the mechanism most frequently used to selectively charge and electrostatically separate two species of different materials such as phosphate and quartz. The ore, composed of small particles of quartz and phosphate, is vibrated on its way from the hopper to the forming chute (Fig. a). Phosphate particles enter the separating zone with a net positive charge while the quartz particles bear a net negative charge. A coal beneficiation system has been developed on the basis of electrostatic separation, where the external field in the separating zone deflects the coal-rich and ash-rich particles in opposite directions towards the collecting-plate compartments.
2. Charging by ion or electron bombardment is used, in which solid particles pass through a corona discharge from a fine wire or a series of needle points positioned parallel to a grounded rotor of the separator. The particles are charged by bombardment with the corona ions. The charged particles rapidly share their charge with the grounded rotor and are thrown from the rotor in a trajectory determined by centrifugal force, gravity, and air resistance. The dielectric or poorly conducting particles lose their charge slowly and are thus held to the surface of the rotor by the image force associated with their surface charge. The well conducting particles are thrown free of the rotor by a combination of centrifugal force and gravity (Fig. b).
3. Charging by conductive induction is a charging mechanism suitable for separating well conducting particles from well insulating particles. A grounded rotor is located close to a positive drum (Fig. c). When conductive particles coming from the hopper pass over the rotor they become negatively charged and attracted toward the positive drum. However, insulating particles fall down by gravity.

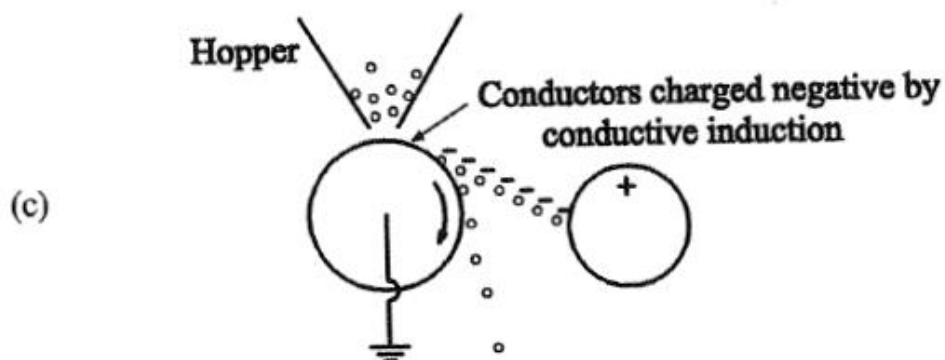
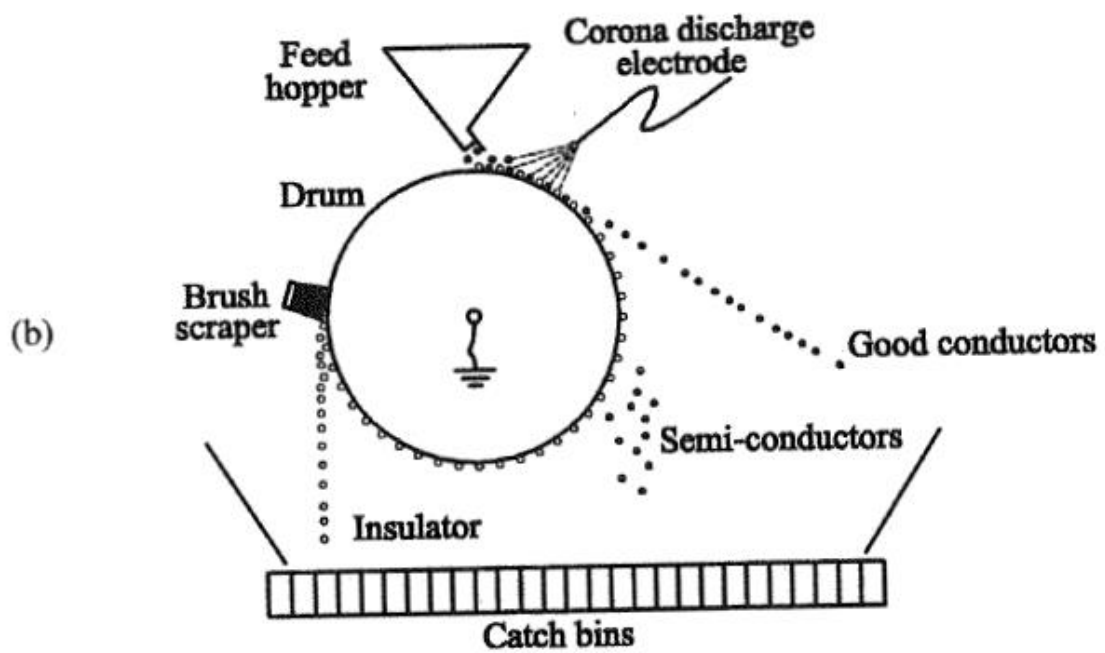
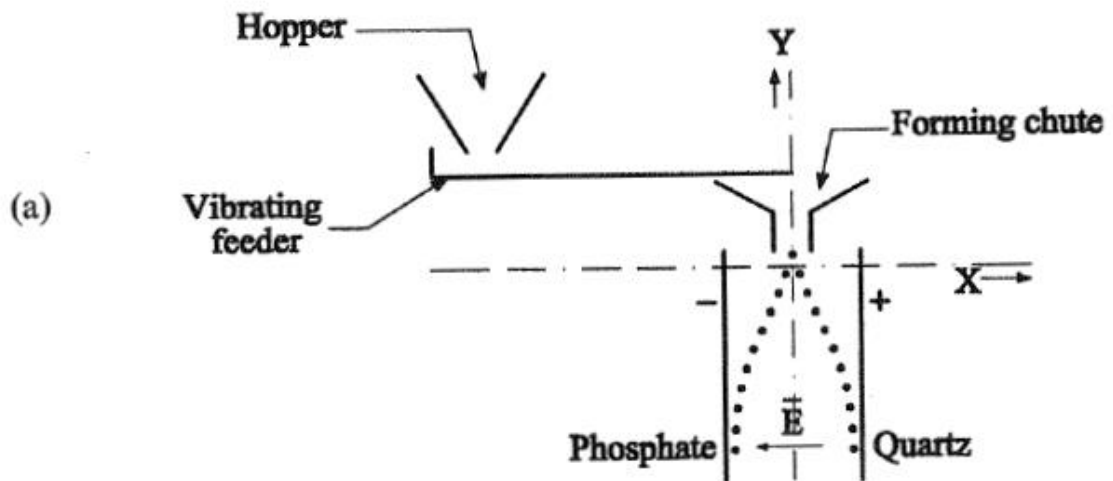


Fig. (a) Electrostatic separator based on charging by contact and frictional electrification.
 (b) Electrostatic separator based on charging by ion or electron bombardment.
 (c) Electrostatic separator based on conductive charging.

Painting / Coating

3. Explain the process of Electrostatic Painting / Coating

This is a kind of electrostatic precipitation of powder or liquid paint on the surface of an object to be coated (or painted).

In liquid paint, a liquid jet issues from the reservoir and extends along the axis of a concentric charging cylinder where a potential V_P is applied between the jet and the cylinder. The jet charges and breaks up into charged droplets while it is in the cylinder. The electric field plus space charge effects between the jet and the grounded object deposit the paint droplets on the surface of the object to be painted, not only on the front side but also on the back side of the object.

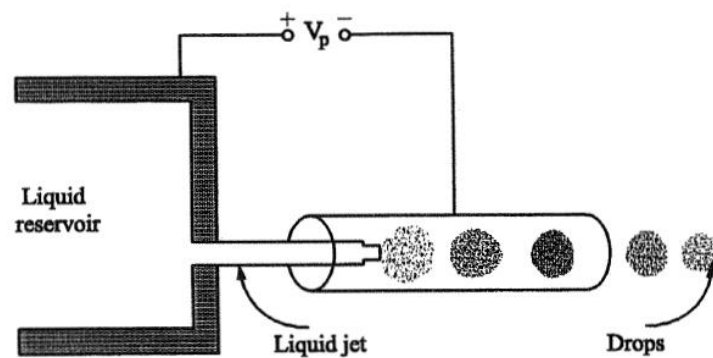


Fig. Schematic diagram of electrostatic generation of liquid droplets for painting

In powder painting, the paint particles are charged by bombardment with corona ions moving under the influence of the prevailing electric field between the corona electrode and the object being grounded. The paint precipitation stops at a certain thickness called the “limiting thickness” because of back discharge which results in craters that impair the quality of finished coat.

In its simplest form, an electrostatic coating operation is visualized as taking place in the following manner. The object to be coated is grounded and supported so that its surface can be approached without obstruction. The coating material, after being charged, is sprayed into the space above the surface in the form of finely divided particles. There is an attraction of the particles to the surface and, as a result, they move toward and accumulate on the surface to form the coating. The various electrostatic coating applications are somewhat sophisticated modifications of this simple situation. They differ from one another in the manner in which the particles are forced, the means by which they are charged, etc.

Electrostatic painting is widely used in the continuous coating lines of automobiles, electric appliances, furniture, and so on.

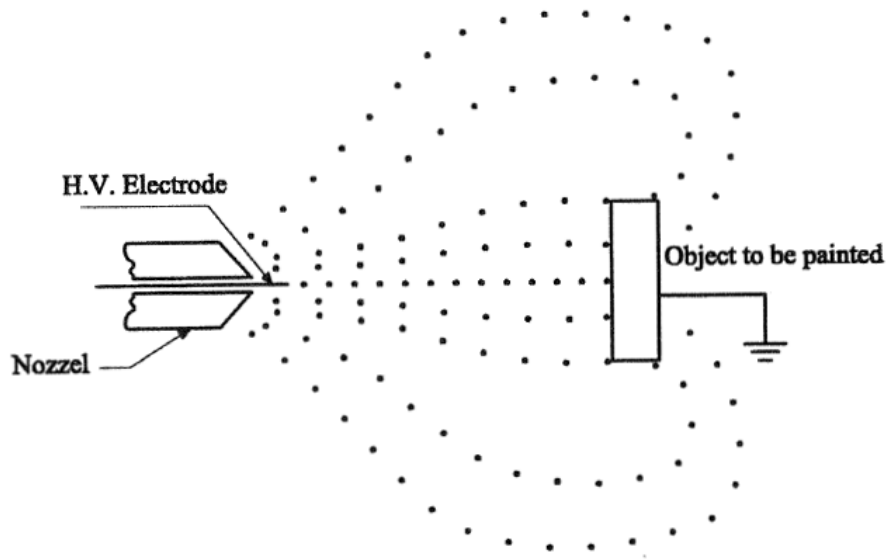


Fig. Electrostatic powder painting

Spraying

4. Write short notes on Electrostatic Spraying.

Conventionally, agricultural pesticides are applied in the form of water based sprays using a hydraulic-atomizing nozzle. The major problem with this method, however, is that a large portion of the spray is lost and the target deposition efficiency is less than 25%. The spray loss and accordingly the deposition efficiency can be attributed to both wind drift out of the target area (exodrift) and deposition to the soil during the process (endodrift).

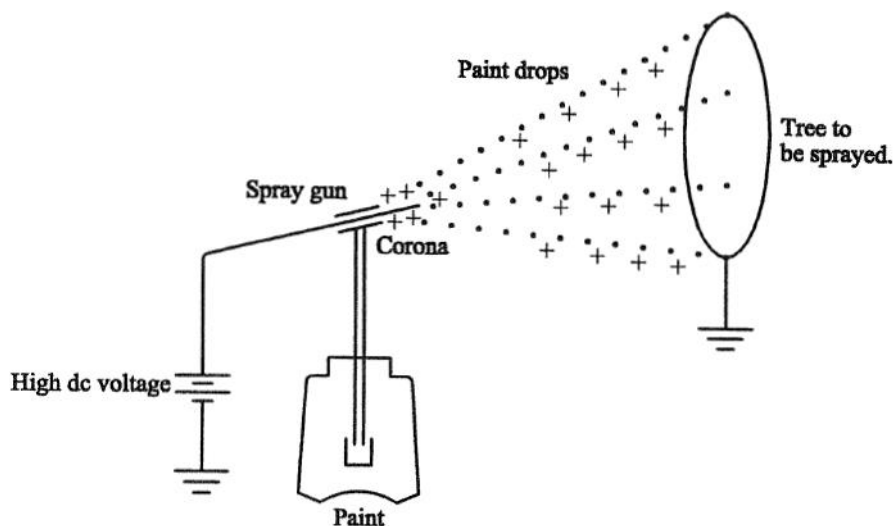


Fig. Electrostatic spraying of trees

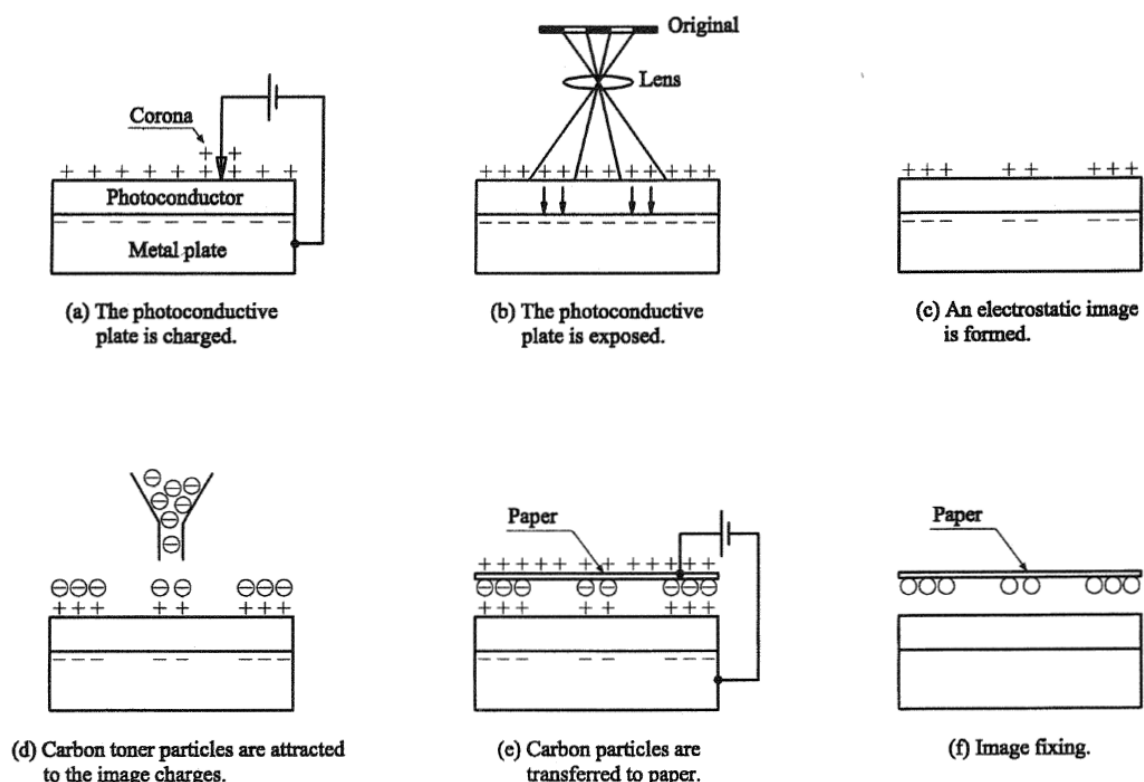
As with industrial coating techniques, electrostatic pesticide spraying technology offers an attractive alternative, which will increase not only the pesticide deposition efficiency but the biological efficacy as well. The reason behind this is the small droplet sizes that can be achieved in electrostatics based systems. That is, in addition to being essential for increasing the biological efficacy, the generation of small droplets will increase the droplet's charge-to-mass ratio. This will, in effect, increase the coulomb force acting on the droplet to a value which is high enough to overcome the mass-dependent gravitational and inertial forces, with a subsequent increase of the deposition efficiency of pesticides.

In pesticide spraying, a nozzle has been developed to generate a concentrated jet which forms an electrified cloud inside the tree foliage., The mutual repulsion of the particles and their coulomb attraction to the leaves (electrically grounded through the tree itself) ensure a superior coverage on both sides of the leaves.

Imaging

5. Describe in detail about the steps to be followed for Electrostatic Imaging.

Electrostatic imaging is a process by which an ordered arrangement of electric charges is deposited on a surface as a latent electrostatic image and subsequently “developed” to convey visual information to an observer.



Consider a system of a metal plate (aluminum) covered by a very thin layer of insulating material (alumina), which in turn is covered by a layer of photoconducting material (selenium). Initially the entire surface of the photoconductor is charged uniformly by a positive charge, as shown in Figure a. The charge on the top surface comes from the positive ions produced by a corona discharge on a wire traveling above the photoconductor. The negative charge on the lower surface comes from the metal plate below and is drawn by attraction to the upper positive charges. Since the photoconductor is an insulator in the dark, the negative charges can get no farther than the bottom of the photoconductor.

When light from the document to be copied is focused on the photoconductor it becomes a conductor, and the negative charges on the lower surface can combine with those of positive polarity on the upper surface to neutralize each other. However, the positive surface charge in dark areas is maintained on the photoconductor (Fig. b). Thus, a “latent” positive charge electrostatic image is produced on the surface of the photoconductor (Fig. c).

Development of the electrostatic image is the process of supplying powder (toner) to the charged areas to provide visibility of the image. The toner particles are charged negatively and attracted to the positive image by reason of the external electric field generated by this image (Fig. d). If a sheet of paper is placed over the development image and sprayed with a positive charge, the electric field penetrating the sheet will act on the negative toner and cause it to transfer to the paper (Fig. e). When the sheet is stripped away from the imaging surface, a well-toned image is still present. A second sheet of paper can then be placed over the image and the transfer process is repeated. Later, the toner is thermally fixed to form a permanent image (Fig. f).

Printing

6. With necessary diagram, explain about Electrostatic Printing.

Many typewriters and computer line printers use so-called impact printing, i.e., characters are cast on metal type, which makes an impact on an ink ribbon to produce prints on paper. New requirements for performance and speed exceed the capabilities of most impact printing technologies. Electrostatic printing is an alternative method.

Electrostatic printers are classified into ink-jet and ink-spray printers. The printing ink is formed into macroscopic droplets which are imaged by electric field, external to the form (print surface). The form serves only as a receptor for the imaged ink droplets and, upon contact, a visible image is instantly produced. This technique is viable on standard forms (sheets of

paper), and no image development or fixing is required. Electrostatic printers are usually known as nonimpact printers.

The ink-jet printing technique produces instantly visible images on standard forms by the electrostatic deflection of charged ink droplets into electrically programmable dot matrix patterns. This principle is analogous to the deflection of electrons in a cathode ray tube. The electrically conducting ink is forced through a nozzle to form a thin jet, which then breaks up into droplets under the influence of surface tension and the mechanical vibrations in the nozzle. At the point where droplets are forming, a high-voltage, field controlled by a computer is applied to the jet to give the newly formed droplets an electric charge related to the signal (Fig.a). This is why the ink-jet printer is known as the charge modulation type of ink printer. The drops then move into a deflection region where a steady transverse electric field deflects them by an amount depending on their acquired charge. This deflection causes them to strike the print surface (usually a piece of paper) at different points, creating an image.

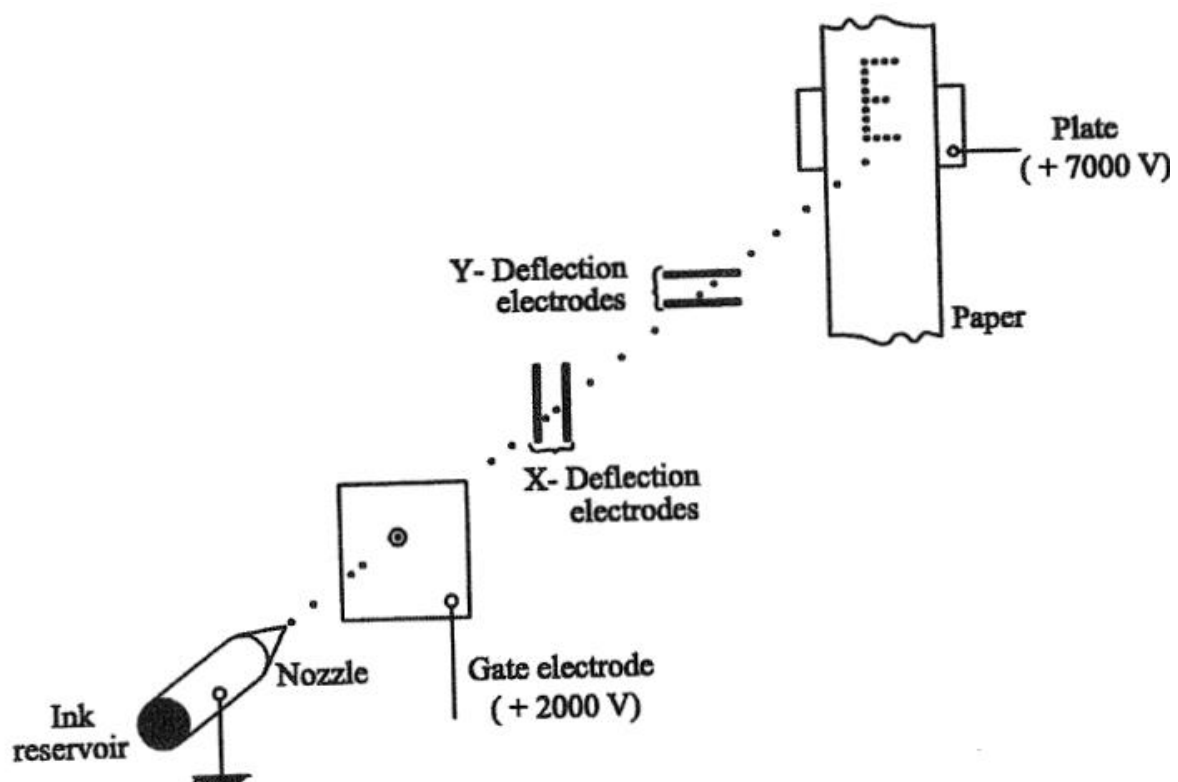


Fig. a. Ink Jet Printer

In the ink-spray printing technique, a reservoir containing the ink is pressurized at a low level (a few centimeters of water) sufficient to form a convex meniscus of ink at the opening of a

vibrating nozzle but not high enough to cause an outflow of ink. The conductive ink, maintained at ground potential, is attracted by the electric field of the gate. When the electrostatic attraction force exceeds the surface tension of the meniscus, droplets are produced. Expressed in terms of potential V , the droplets are produced when the potential between the gate electrode and the meniscus is

$$V > 2D(\gamma/\epsilon d)^{0.5}$$

where γ = ink surface tension, ϵ = ink permittivity, d = nozzle orifice diameter, and D = distance between orifice and gate. The droplets are accelerated and then imaged into the desired dot-matrix format by electrostatic deflection. Since the droplets are produced with a nearly uniform specific charge, programmable deflection is obtained by varying the magnitude of the deflection field. This is accomplished by electronically controlling the voltage applied to the deflection electrodes (Fig. b). This is why the ink-spray printer is known as the field-modulation type of ink printer. Two sets of electrodes are employed to obtain both horizontal and vertical deflection, to allow for printing on stationary forms.

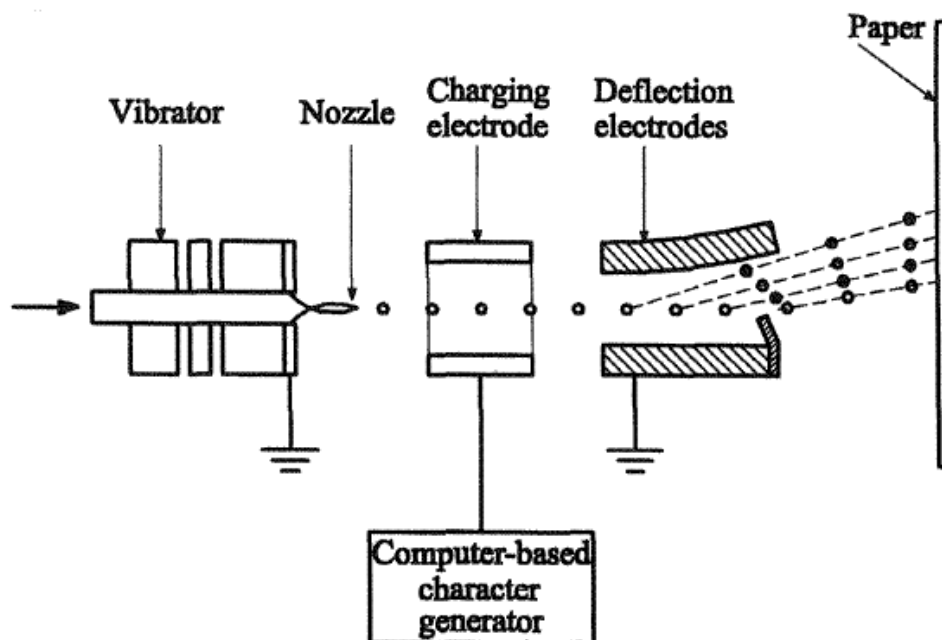


Fig. b. Ink Spray Printer

Since the droplets are very small they can be quickly accelerated and are able to produce high-quality hard copy much faster than electronic (impact) printers. There are commercially available electrostatic printers with capabilities of printing in excess of 30,000 lines/minute. With the current concern for noise from impact printers, electrostatic printers have a definite

advantage as the level of noise is only that generated by the hardly visible droplets of ink landing on the paper.

Transport of Materials

7. With neat sketch write short notes on Electrostatic Transport of Materials.

The feasibility of electrostatic transport of light materials which triboelectrify themselves on a stationary “conveyor” belt, as shown schematically in Figure, appears very promising. The three-phase high-voltage supply U-V-W generates a traveling field at the surface of the conveyor. The charged particles will be transported along the field. The electrostatic conveying is independent of the sign of the charge; thus, both positively and negatively charged particles will transport in the same direction.

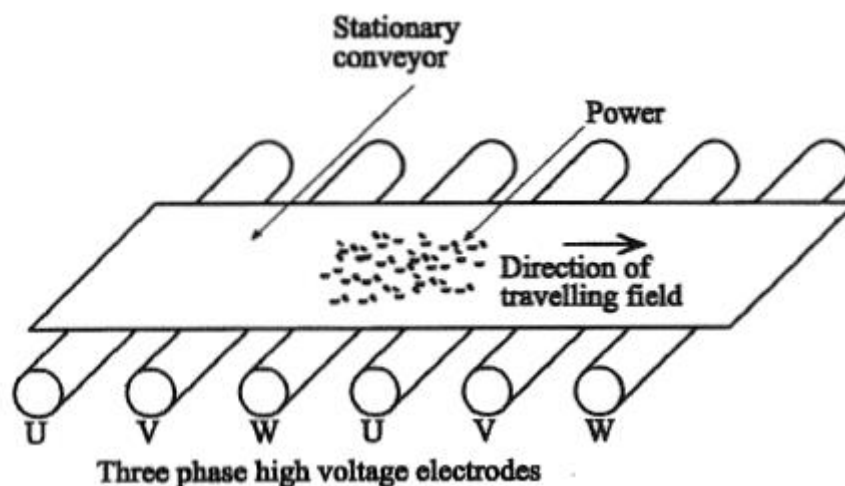


Fig. Electrostatic conveying of tribo-electrified materials

Manufacturing of Sand Paper

8. Briefly explain the process of Manufacturing of Sand Paper.

Another example of what electrostatics can do for industry is evidenced in the lining up and gluing of billions of particles in the right position, with a uniform distribution as shown in Figure. Abrasive particles of quartz, silicon carbide, diamond, etc. are poured onto a continuous conveyor or belt. As they arrive in the strong electric field between two parallel electrodes stressed by a voltage up to 100 kV, they line up along the field lines with sharp points facing the electrodes. The electric charge which they acquire from the semiconducting belt causes them to be propelled and implanted in the adhesive. Any particle which strikes an area already fully covered by other particles falls back and is recovered for reprocessing as surplus abrasive

material.

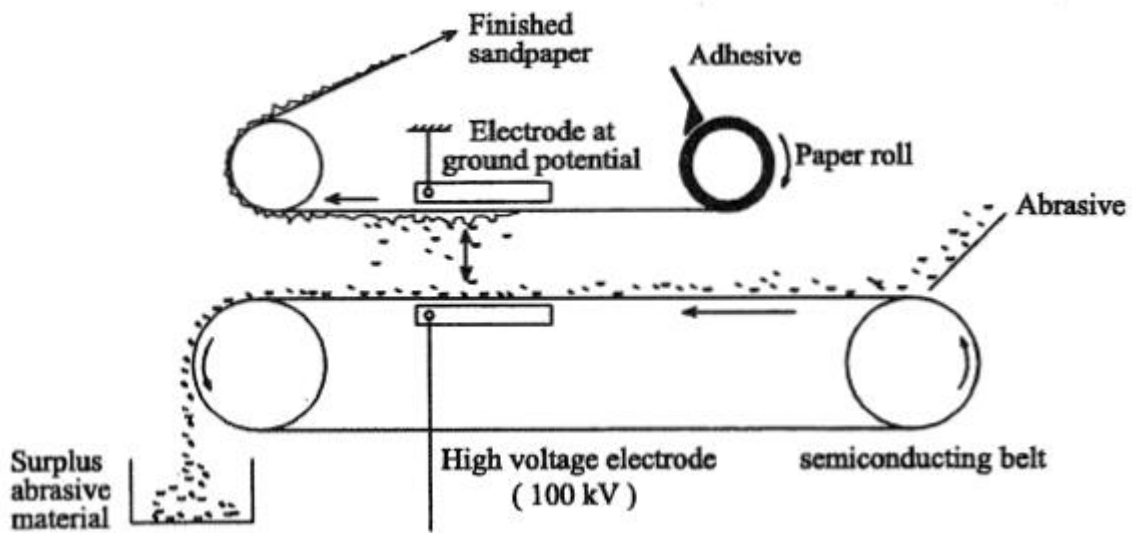


Fig. Principle of electrostatic manufacture of sandpaper

Smoke Particle Detector

9. Explain about the Smoke Particle Detector.

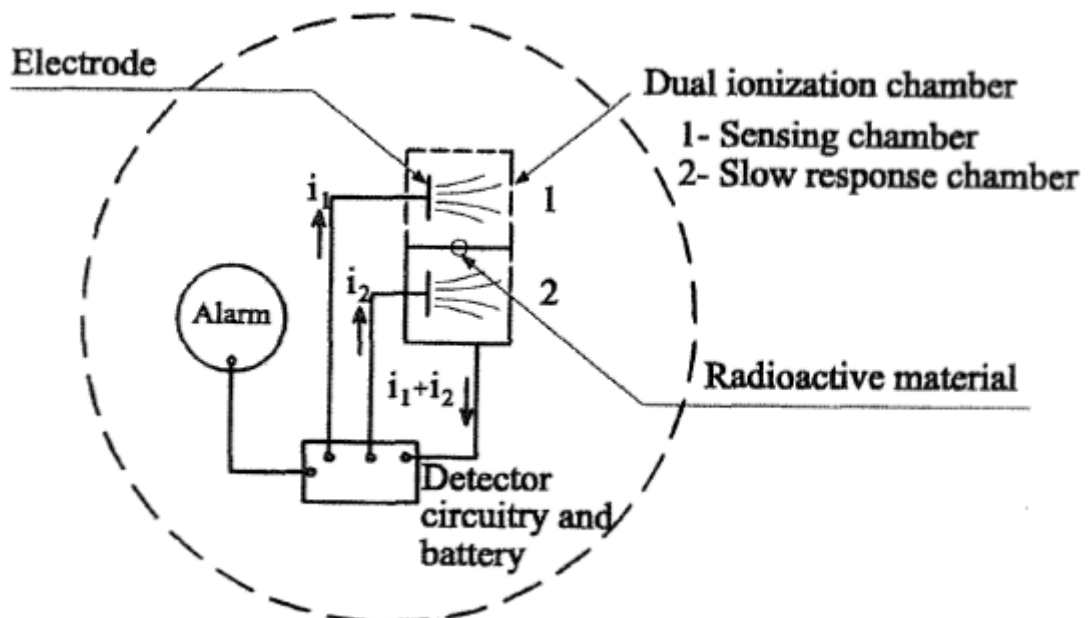


Fig. Smoke particle detector

The design of such detectors is based on the fact that electrically charged particles of smoke have substantially lower mobility than ions. During the normal surveillance periods, two continuous and equal ion currents i_1 and i_2 flow through the air of the two chambers made

conductive by radiation from a radioactive material. The current i_1 flows in the sensing chamber whose walls have so many holes that smoke particles flow in easily, in contrast to the low-response chamber. In large chambers, the radioactive material may be replaced by a corona source of ions for sensitive detection of smoke particles. A sudden increase in the number of smoke particles in the ambient will be followed by an immediate increase in the particle density in the sensing chamber and by a slower increase in the corresponding particle density in the second chamber. The current i_2 will decrease on account of the attachment of ions to the smoke particles. The decrease is more than sufficient to actuate the solid-state circuitry, which sounds the alarm. Nowadays, the low cost of smoke detectors has made them accessible to practically everyone interested in acquiring a warning device, which undoubtedly will save lives.

Electrostatic Spinning

10. With neat sketch write short notes on Electrostatic Spinning.

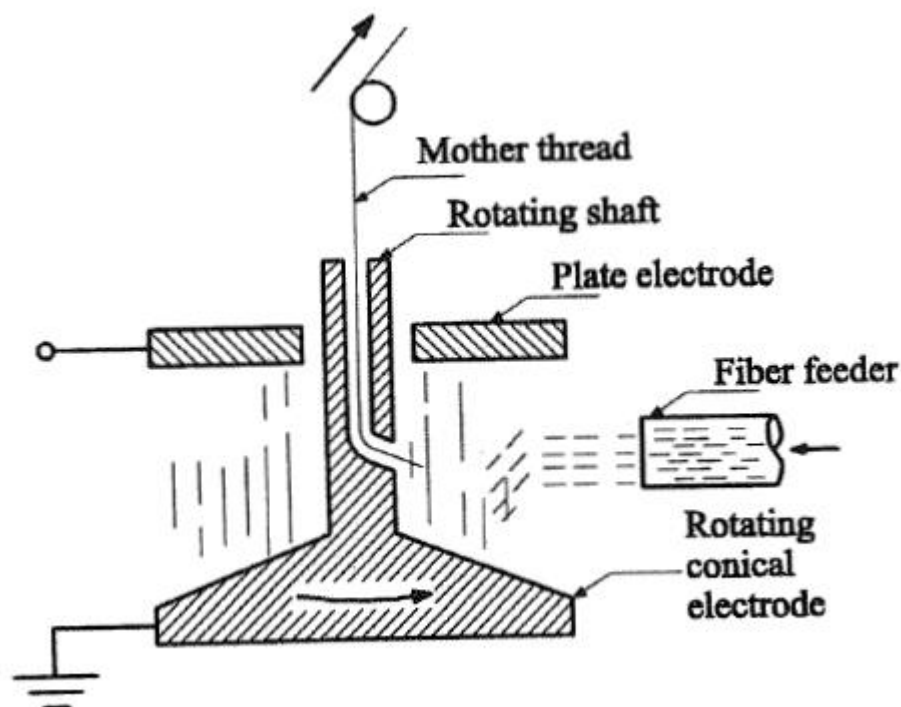


Fig. Electrostatic Spinning

Figure shows a schematic of an electrostatic device to make a thread from fibers with minimum use of air to avoid quality degradation due to contamination of particles. The air-conveyed fibers are fed from a feeder into a high-voltage DC field between the gap plate and conical electrodes and are aligned along the field lines. At the same time they are attracted towards the rotating shaft by a gradient force caused by the narrowing gap. A mother thread is inserted

from the top of the rotating shaft into its hole to grasp the vertically aligned fibers. When it is pulled upwards, the fibers are pulled into the hole to be spun continuously to produce a thread.

Pumping

11. Write short notes on Electrostatic Pumping.

In high-voltage power equipment, the current-carrying components must be cooled to carry away the heat caused by ohmic losses. Generally, the fluids are more effective in cooling when they make direct contact with the high voltage conductors, but this requires that they must be electrical insulators such as oils. The coolant must also circulate to carry away the heat, so some means of pumping by thermal convection or mechanical pumps is generally included. A more effective method in coolant circulation is based on the force transmitted to the cooling fluid by charges in a high-voltage field. This electrohydrodynamic pumping has been known for some time, but practical implementation in a transformer and in a cable has been reported.

Propulsion

12. With neat sketch discuss in detail about Electrostatic Propulsion.

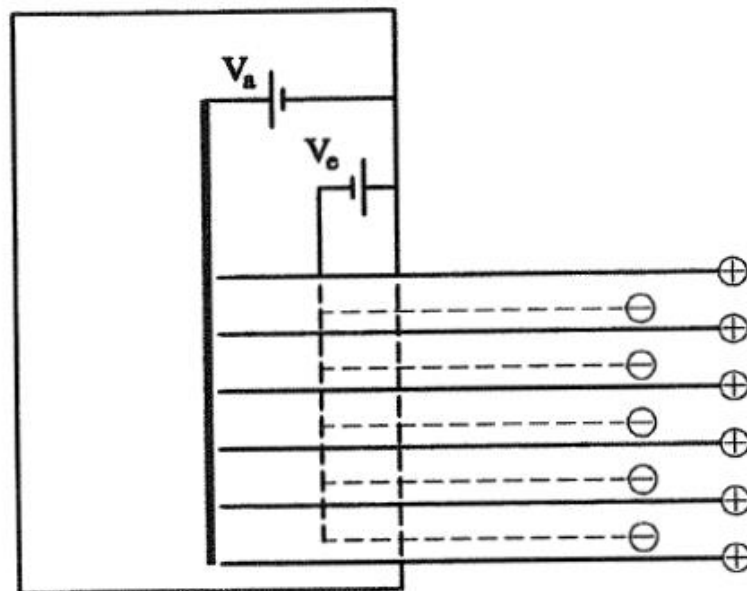


Fig. Electrostatic propulsion concept

An ordinary rocket engine propels the rocket forward by ejecting fuel backwards. The propulsion force F obtained is expressed as

$$F = \frac{d}{dt}mv = v \frac{dm}{dt}$$

where dm/dt is the rate of ejection of the propellant and v is the ejection velocity, which is constant. For chemical fuel, the ejection velocity may be supersonic, of the order of 10^3 m/s. It is difficult to achieve much higher velocities using chemical fuels.

Electrostatic propulsion uses ionized particles as propellant. The particles are accelerated by electrostatic force to a much higher velocity. Thus, for the same propulsion force, electrostatic propulsion consumes less mass than a chemical engine does.

Figure illustrates the basic operating principle of electrostatic propulsion. Propellant enters the ionization chamber, where it is ionized either by heat or by bombardment with electrons. Positive ions are accelerated and ejected through the screen. Electrons are absorbed by the anode. These electrons must also be ejected with the positive ions at the same velocity; otherwise, the rocket will be increasingly negatively charged.

The velocity of the positive ion v_i is given by

$$v_i = \sqrt{\frac{2q_i V_a}{m_i}}$$

where q_i is the charge on the positive ion and m_i is its mass. V_a is the accelerating voltage for positive ions, which may reach several tens of kilovolts.

Similarly, the velocity of the electron v_e is given by

$$v_e = \sqrt{\frac{2q_e V_e}{m_e}}$$

where $q_e = 1.6 \times 10^{-19}$ C and $m_e = 9.11 \times 10^{-31}$ kg.

To neutralize the ejected ion, v_e must be equal to v_i . Thus, the voltages V_a and V_e must be related by the following equation

$$V_a/m_i = V_e/m_e$$

In equation (19.3), it is assumed that the ions carry a single positive charge. Because $m_i \gg m_e$, $V_a \gg V_e$.

To estimate the magnitude of the propulsion force in terms of the ion current I , being related to the density of ions n_i as

$$I = n_i v_i q_i A = dq_i/dt$$

where A is the cross-section of the ion beam, the rate of mass ejection is

$$\frac{dm_i}{dt} = n_i v_i m_i A$$

Thus, the propulsion force F is expressed as

$$F = v_i \frac{dm_i}{dt} = \frac{v_i m_i I}{q_i}$$

Electrostatic propulsion is used on synchronous satellites to adjust their position and to adjust antenna orientations. It is potentially useful for exploring deep space because of the large propulsion force-to-fuel ratio as compared with chemical engines.

Ozone Generation

13. With neat sketch discuss in detail about Ozone Generation.

Ozone is a virtually colorless gas with an acrid odor and very strong oxidizing properties. Ozone is very toxic to humans and animals, causes serious damage to plant life, and produces deterioration in many materials. Ozone is the triatomic form of oxygen that has been formed by recombining highly excited oxygen atoms or molecules with one another. Unlike other agents such as chlorine, oxidation with ozone leaves no toxic residues that have to be removed and disposed of because the process yields only “oxygenated” products and oxygen. In practice, ozone is completely nonselective and immediately starts to oxidize everything it comes into contact with. This property makes it a very powerful bactericide and viricide as well as a strong bleaching agent. The ozone molecule is only moderately stable and, in the absence of oxidizable substances, will decay to form stable diatomic oxygen. The instability of ozone has the consequence that it can be neither stored nor transported over distances requiring long periods of time. This means it must be produced on site when and where it is required, which has the added environmental and safety advantages of not having to store or transport potentially dangerous chemicals in large quantities.

The traditional way of producing ozone is by means of dielectric barrier discharge or so-called silent electrical discharge. Dry feed gas (either oxygen or air) is passed through a narrow discharge gap. One side of the gap is formed by a grounded electrode, the other by a dielectric, normally glass, in contact with a high-voltage electrode. When high voltage at high frequency is applied to the high-voltage electrode, ozone is produced in the feed gas by micro discharges taking place in the discharge gap.

Ozone has many applications in industry. Among these applications are sterilization processes and control of microbials, purification of drinking water, and treatment of waste water instead

of the use of chlorine, control of survival rate of farmed fishes, cleaning, deodorization, and making healthy indoor air, deNO_x, and deSO_x, processes by eliminating these hazardous pollutants from flue gases, ozone therapy, and protection of the earth's surface from dangerous ultraviolet radiation.

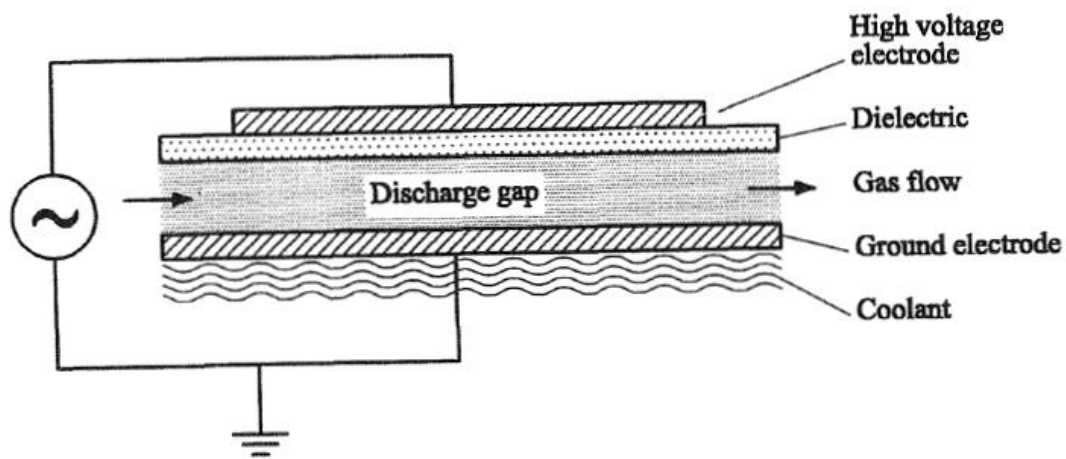


Fig. Electrode configuration of silent or dielectric-barrier discharge

Biomedical Applications

14. Describe the various applications of high voltage in the field of Biomedical.

There are needs in biotechnology for the manipulation of small objects, such as cells, chromosomes, biological membranes, and nucleic acid and protein molecules. Biological cells range in size from less than a micrometer to several hundred micrometers, and molecules are even smaller, measured in nanometers. High-voltage electrostatic forces are highly suitable for handling, characterization, and separation of these fine particles. With the use of electrostatic effects, these objects can be manipulated collectively or even individually. In addition, because the electrostatic force is a “surface force” distributed around the surface of an object, it enables gentle manipulation without applying too much stress to the object.

Another aspect of electrostatic effects is associated with the breakdown of membranes. When a pulsed electric field of moderate magnitude is applied, a cell membrane breaks down and becomes permeable, but a resealing process followed due to the fluidity of the membrane. This process is called “reversible breakdown” and is used for bringing foreign material into the cell interior. In particular, when this process is conducted in a DNA solution, it can be used to inject foreign genes into the cells (transfection). Alternatively, when a partial breakdown occurs at the contact point of two cells, they may fuse into one, to yield a hybrid between these two cells (electrical cell fusion). On the other hand, if the pulse is too strong, irreversible breakdown takes place and the cell is destroyed. This effect can be used for sterilization.