1. What are the different types of over voltages? (May 2013)(May 2015)
   Lightning over voltages, Switching over voltages, and power frequency over voltages (temporary over voltage).

2. Explain the various regions of the cloud.
   The upper regions of the cloud are positively charged, whereas the lower region and the base are predominantly negative except the local region near the base and the head which is possible.

3. What is back flash over? (Dec 2016)
   When a direct lightning strike occurs on a tower, the tower has to carry huge impulse currents. If the tower footing resistance is considerable, the potential of the tower rise to a large value, steeply with respect to the line and consequently a flash over may take place along the insulator strings. This is known as back flash over.

4. State the parameters and the characteristics of the lightning strokes. (May 2015)
   Amplitude of the current, the rate of rise, the probability distribution of them and the wave shapes of the lightning voltages and currents.

5. How are attenuation and distortion caused?
   Attenuation is caused due to the energy loss in the line and distortion is caused due to the inductance and capacitance of the line.

6. State the factors influence the lightning induced voltages on transmission lines. (Nov 2015)
   The ground conductivity, the leader strokes current and the corona.

7. State the attenuation and distortion of traveling waves.
   The decrease in the magnitude of the wave as it propagates along the line is called attenuation. The elongation or change of wave shapes that occur is called distortion.

8. When over voltages are generated in EHV system?
   Over voltages are generated in EHV systems when there is a sudden release of internal energy stored either in the electrostatic form or in the electromagnetic form.

9. What are the uses of shunt reactors?
   Shunt reactors are (i) Used to limit the voltage rise due to the ferranti effect (ii) Used to reduce surges caused due to sudden energizing.
10. What is a ground wire?
The 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.

11. What is an expulsion gap?
Expulsion gap is a device, which consists of a spark gap together with an arc quenching device, which extinguishes the current arc when the gap breaks over due to over voltage.

12. What is a protector tube?
It is a device, which 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.

13. How is the insulation level and the protective safety margin arrived?
Selecting the risk of failure, the statistical safety factor and by firing the withstand level of any equipment or apparatus corresponding to 90% or 95% of the withstand voltage.

14. Mention the various insulation levels in a substation?
The bus bar insulation is the highest to ensure the continuity of supply in a substation. The circuit breakers, isolators, instrument and relay transformers are given the next lower limiting level. The power transformers are the costliest and sensitive devices and the insulation level for it is the lowest.

15. What are the various types of surge arresters used for EHV and UHV systems?
Silicon carbide arresters with spark gaps, Silicon carbide arresters with current limiting gaps and the gapless metal oxide arresters.

16. Write the equation of surge admittance and surge impedance of the transmission line.
\[
\begin{align*}
Y(S) & = \frac{C}{L} \left( \frac{(S+\alpha)(S+\alpha)}{\beta(S+\alpha)} \right)^{1/2} \\
Z(S) & = \frac{L}{C} \left( \frac{(S+\alpha)(S+\alpha)}{\beta(S+\alpha)} \right)^{1/2}
\end{align*}
\]
where \(\alpha\) is the attenuation constant and \(\beta\) is the wavelength constant.
17. Define Isokeraunic level or thunderstorm days. (May 2011, Dec 2016).
   It is defined as the number of days in a year when the thunder is heard or
   recorded in a particular location. Often it does not distinguish between the
   ground strokes and the cloud-to-cloud strokes.

18. A transmission line surge impedance 250 ohms is connected to a cable of surge
    impedance of 50 ohms at the other end, if the surge of 400 kV travels along the line
    to the junction point, find the voltage build at the junction. (May 2011).
    \[ V'' = V(2Z2/Z1+Z2), \]
    where \( V = 400 \text{ kV} \), \( Z1 = 250 \text{ ohms} \),
    \( Z2 = 50 \text{ ohms} \)
    \[ V'' = 400,000 \times (2(50)/(250+50)), \]
    \[ V'' = 133.33 \text{ kV}. \]

19. Define Lightning phenomenon. (Dec 2012)
   Lightning phenomenon is a peak discharge in which charge accumulated in
   the cloud discharges into a neighboring cloud or on the ground.

20. List some sources causing switching surges. (Dec 2012)
   Sudden switching off of loads, short circuits and fault clearances,
   disconnection of unloaded transformers, reactors.

21. What is stepped leader stroke? (May 2013)
   Due to insufficient build of charge at the head of leader stroke comes to a halt
   after progressing about 50 meter and again after a short interval the streamer
   starts out repeating its performance with different branches by a series of jumps.
   It is called as stepped leader.

22. State the sources which determine the wave shape of switching surges. (Nov
    2013)
    - 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.

23. Write down the causes of power frequency over voltages. (Nov 2013)
   The main causes for power frequency and its harmonic over voltages are,
   - Sudden loss of loads,
   - Disconnection of inductive loads or connection of capacitive loads,
   - Ferranti effect, unsymmetrical faults, and
   - Saturation in transformer

24. Classify the lightning strokes. (May 2014)
    - Cloud to cloud lightning
    - Cloud to air lightning
    - Intra cloud lightning
Cloud to ground lightning
Bolt from the blue
Ribbon lightning

25. Why a simple spark gap cannot offer full protection against overvoltages? (Nov 2015)

The sparkover voltage of a rod gap depends on the atmospheric conditions. There is no current limiting device provided so as to limit the current after sparkover, and hence a series resistance is often used. Without a series resistance, the sparking current may be very high and the applied impulse voltage suddenly collapses to zero thus creating a steep step voltage, which sometimes proves to be very dangerous to the apparatus to be protected, such as transformer or the machine windings.
UNIT - 1
PART - B


The different situations under which switching over voltages happens are

- 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 6f 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 over voltages.

The different situations under which power frequency over voltages happens are

- Sudden loss of loads,
- Disconnection of inductive loads or connection of capacitive loads,
- Ferranti effect, unsymmetrical faults, and
- Saturation in transformers.

The over voltages due to switching and power frequency may be controlled by

- Energization of transmission lines in one or more steps by inserting resistances and withdrawing them afterwards,
- Phase controlled closing of circuit breakers,
- Drainage of trapped charges before reclosing,
- Use of shunt reactors, and
- Limiting switching surges by suitable surge diverters

(All the above causes and control methods should be explained in detail)

2. Explain with suitable figure the principles and functioning of (i) Expulsion Gap (ii) Protector Tube.

(i) Expulsion Gap

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, drivey away the arc products and ionized air. When the follow-on power frequency current passes through zero value, the arc is extinguished and the path becomes open circuited. Meanwhile the insulation recovers its dielectric strength, and the normal conditions are established. The lightning and follow-up power frequency currents together can last for 2 to 3 half cycles only. Therefore, generally no disturbance in the network is produced. For 132 or 220 kV lines, the maximum current rating may be about 7,500 A.

(ii) Protector Tube

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. Usually, the flashover voltage of the protector tube is less than that of the line insulation, and hence it can discharge the lightning overvoltage effectively.
3. Write short a note on (i) Rod gaps as protective devices (ii) Ground wires for protection of overhead lines. (Nov 2014)

(i) Rod gaps as protective devices

Construction, working and limitations of rod gap arrester should be explained in detail.

(ii) Ground wires for protection of overhead lines

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, as the current path is in three directions. The instantaneous potential to which tower top can rise is

\[
V_T = \frac{I_0 Z_T}{1 + \frac{Z_T}{Z_S}}
\]

where,

\(Z_T\) = surge impedance of the tower, and

\(Z_S\) = surge impedance of the ground wire.

4. What are the mechanisms by which lightning strokes develop and induce over voltages on overhead power lines? Give the mathematical models for lightning discharges and explain them. (May 2013, Dec 2016)
Lightning mechanism

When the electric field intensity at some point in the charge concentrated cloud exceeds the breakdown value of the moist ionized air (\( \sim 10 \) 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 jous, the streamer again starts out repeating its performance. The total time required for such a stepped leader to reach the ground may be 20 ms. The path may be quite lustrous, depending on the local conditions in air as well as the electric field gradients. Branches from the initial leader may also be formed. Since the progress of this leader stroke is by a series of jumps, it is referred as stepped leader. The picture of a typical leader stroke taken with a Boy's camera is shown in Fig.

![Propagation of a stepped leader stroke from a cloud](image)

The lightning stroke and the electrical discharges due to lightning are explained based on the "streamer" or "kanel" theory for spark discharges in long gaps with non-uniform electric fields. The lightning consists of few separate discharges starting from a leader discharge and culminates in return strokes or main discharges. The velocity of the leader stroke of the first discharge may be $1.5 \times 10^7$ cm/s, of the succeeding leader strokes about $10^8$ cm/s, and of the return strokes may be $1.5 \times 10^9$ to $1.5 \times 10^{10}$ 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 jis or more. The diameters of the return strokes were estimated to be about 1 to 2 cm 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. A Boy's camera picture of return stroke is shown in Fig.

![Development of the main or return stroke](image)
After the completion of the return stroke, a much smaller current of 100 to 1000 A may continue to flow which persists approximately 20 ms. Due to these currents the initial breakdown points in the cloud are considerably reduced and discharges concentrate towards this point. Therefore, additional reservoirs of charge become available due to penetration of a cloud mass known as preferred paths and lead to repeated strokes. The leader strokes of the repeated strokes progress with much less velocity (≈1% of that of light) and do not branch.
This stroke is called continuous leader, and return stroke for this leader follows with much less current. The interval between the repeated strokes may be from 0.6 ms to 500 ms with an average of 30 ms. Multiple strokes may last for 1 s. The total duration of the lightning may be more than 1 s. The current from the ground by the main return stroke may have a peak value of 250,000 A.

During the charge formation process, the cloud may be considered to be a non-conductor. 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 where in 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 \( I/Q \) with a 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

\[
V = IZ = I_0 \frac{ZZ_0}{Z + Z_0} = I_0 \frac{Z}{1 + \frac{Z}{Z_0}}
\]

The source impedance of the lightning channels are not known exactly, but it is estimated to be about 1000 to 3000 ft. The objects of interest to electrical engineers, namely, transmission line, etc. have surge impedances less than 500 Ω (overhead lines 300 to 500 Ω, ground wires 100 to 150 Ω, towers 10 to 50 Ω, etc.). 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.

If a lightning stroke current as low as 10,000 A strikes a line of 400 Ω surge impedance, it may cause an overvoltage of 4000 kV. This is a heavy overvoltage and causes immediate flashover of the line conductor through its insulator strings. In case a direct stroke occurs over the top of an unshielded transmission line, the current wave tries to divide into two branches and travel on either side of the line. Hence, the effective surge impedance of the line as seen by the wave is \( Z_0/2 \) and taking the above example, the overvoltage caused may be only 10,000 x (400/2) = 2000 kV.

If this line were to be a 132 kV line with an eleven 10 inch disc insulator string, the flashover of the insulator string will take place, as the impulse flashover voltage of the string is about 950 kV for a 2µs front impulse wave. 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) known as “Isokeraunic Level” defined as the number of days in a year when thunder is heard or recorded in a particular location. But this indication does not often distinguish between the ground strikes and the cloud-to-cloud strikes. If a measure of ground flashover density
\((N_g)\) is obtained, then the number of ground flashovers can be computed from the TD level. From the past records and the past experience, it is found that

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

It is reported that TD is between 5 and 15 in Britain, Europe and Pacific west of North America, and is in the range of 30 to 50 in Central and Eastern states of U.S.A. A much higher level is reported from South Africa and South America. No literature is available for the different regions in India, but a value of 30 to 50 may be taken for the coastal areas and
for the central parts of India.
5. Explain the different theories of charge formation in clouds. (May 2011) (Dec 2012)

Lightning phenomenon is a peak discharge in which charge accumulated in the clouds discharges into a neighbouring cloud or to the ground.

**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 centres probably at a distance of about 300 to 2000 m.
- The volume of the clouds that participate in lightning flashover are uncertain, but the charge inside the cloud may be as high as 1 to 100 C.
- Clouds may have a potential as high as 107 to 108 V with field gradients ranging from 100 V/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.
(a) Simpson’s theory

According to the 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.

(b) Mason’s theory

According to Mason,

- The ice splinters should carry only positive charge upwards.
- Water being ionic in nature has concentration of \( \text{H}^+ \) and \( \text{OH}^- \) 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 \( \text{H}^+ \) 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.
- Hence, it must be appreciated, that the outer shells of the freezeed 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.
6. An underground cable of inductance 0.150 mH/km and of capacitance 0.2 µF/km is connected to an overhead line having an inductance of 1.2 mH/km and capacitance of 0.006 µF/km. Calculate the transmitted and reflected voltage and current waves at the junction, if a surge of 200 kV travels to the junction, (i) along the cable, and (ii) along the overhead line. (May 2011).

   Surge impedance of the cable = 27.4 ohms
   Surge impedance of the line = 447.2 ohms

For surge travels along the cable:
   Coefficient of reflection = 0.885
   The reflected wave = 176.91 kV
   The transmitted wave = 377 kV
   The reflected current wave = 6.46 kA
   The transmitted current wave = 0.84 kA

For surge travels along the line:
   Coefficient of reflection = -0.885
   Reflected wave = -177 kV
   Transmitted wave = 23 kV
   Reflected current wave = 0.84 kA
   Transmitted current wave = 0.396 kA

7. A long transmission line is energized by a unit step voltage 1.0 V at the sending end and is open circuited at the receiving end. Construct the Bewley lattice diagram and obtain the value of the voltage at the receiving end after a long time. Take the attenuation factor α = 0.8. Discuss the step by step procedure for constructing Bewley’s Lattice diagram with an example. (May 2014, Nov 2015)
(a) Equivalent circuit

(b) Lattice diagram

Z_s = 0  Scolding end  Z  Receiving end  Z_L = \infty

\( a = 0 \)  \( a = -1 \)  \( a = 1 \)  \( b = 2 \)

\( u(t) \)

1.0

0  0.64  0.80  0.80
2  -0.64  -0.512  -0.512
4  -0.0096  -0.327  -0.327
6  0.0096  0.327  0.327

\( \alpha = 0.8 \)
8. Draw the cross sectional view of valve type lightning arrester and explain its operation with V-I characteristics. (May 2014)

9. What are the requirements of a ground wire for protecting power conductors against direct lightning stroke? Explain how they are achieved in practice. (May 2014)

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, as the current path is in three directions. The instantaneous potential to which tower top can rise is

\[ V_T = \frac{I_D Z_T}{1 + \frac{Z_T^2}{Z_S}} \]

where,

- \( Z_T \) = surge impedance of the tower, and
- \( Z_S \) = surge impedance of the ground wire.

10. Explain the characteristics of switching surges with typical waveforms. Explain
A steep-fronted surge waveform are more vulnerable to insulation? (May 2015)
The waveshapes of switching surges are quite different and may have origin from any of the following sources.

(i) De-energizing of transmission lines, cables, shunt capacitor, banks, etc.
(ii) Disconnection of unloaded transformers, reactors, etc.
(iii) Energization or reclosing of lines and reactive loads.
(iv) Sudden switching off of loads.
(v) Short circuits and fault clearances.
(vi) Resonance phenomenon like ferro-resonance, arcing grounds, etc. Typical waveshapes of the switching surges are given in Figs. 8.16a to (e).

From the figures of the switching surges it is clear that the overvoltages are irregular (oscillatory or unipolar) and can be of high frequency or power frequency with its harmonics. The relative magnitudes of the overvoltages may be about 2.4 p.u. in the case of transformer energizing and 1.4 to 2.0 p.u. in switching transmission lines.

(a) Recovery voltage after fault clearing
(b) Fault initiation
(c) Overvoltage at the line end after fault clearing
(d) Energization of long transmission line
(e) Overvoltage at line end during (d)
For steep fronted travelling waves, the voltages at different points in the sub-station can exceed the protective level by amounts that depend on the distance from the diverter location, the steepness of the wave front and other electrical parameters. Hence, it is necessary to decide the number of locations at which surge diverters are to be located and their ratings. It is necessary to keep this number to a minimum. Also, care must be taken regarding switching overvoltages generated due to current chopping which may destroy the transformer or the equipment near the circuit breakers. The Basic Impulse Level (BIL) is often determined as simply 1.25 to 1.30 times the protective level offered by the surge diverter. Usually, the next higher BIL value from the standard values is chosen. This is quite sufficient for smaller stations and station ratings up to 220 kV. For bigger stations and stations of importance, the “distance effect” discussed in the next section is to be suitably allowed for when surge diverters are to be used for SIL also; a margin of 15 to 20% is normally allowed over the protective level. Distance effect is negligible for long fronted switching surges.

11. What are the different method employed for the lightning protection of overhead lines? (Dec 2016)

There are three methods used to protect the overhead lines from the lightning. In the first method the tower footing resistance is reduced by using some special arrangements, so that during the lightning strike the impulse current will be evenly distributed to the ground. The methods used for this purpose are, i) counterpoised wires ii) ground rods. (explain about counterpoised wire and ground rods)

In the second method ground or shield wire are used to prevent the transmission lines form the lightning strike. (refer question 9)

In the third method protective devices like Expulsion gaps, Rod gaps and Lightning arresters are used to prevent the damage due to lightning. (refer question 2 and 8)