KDK COLLEGE OF ENGINEERING

Department OF Electrical Engineering

HIGH VOLTAGE ENGINEERING

UNIT 2

LECTURE NOTES

UNIT 2 Lighting and Switching Overvoltages.

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 special attention towards the protection of transmission lines and power apparatus from the chief causes of overvoltages in electric systems, namely lightning overvoltage and switching overvoltage. Lightning overvoltage is a natural phenomenon, while switching over voltages originate in the system itself by the connection and disconnection of circuit breaker contacts or due to initiation or interruption of faults. Switching over voltages are highly damped short duration overvoltage. They are "temporary overvoltage" of power frequency or their harmonic frequencies either sustained or weakly damped and originate in switching and fault clearing processes in power systems. Although both switching and power frequency over¬ voltages have no common origin, they may occur together, and their combined effect is important in insulation design. Probability of lightning and switching overvoltage coinciding together is very small and hence can be neglected. 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. Hence, there is a system operating voltage at which the emphasis changes from lightning to switching surge design, this being important above 500 kV. In the range of 300 kV to 765 kV, both switching overvoltage's and lightning overvoltage have to be considered, while for ultra high voltages (> 700 kV), perhaps switching surges may be the chief condition for design considerations.

For the study of overvoltage a basic knowledge of the origin of overvoltage, surge phenomenon, and its propagation is desirable.

NATURAL CAUSES FOR OVERVOLTAGES — LIGHTNING PHENOMENON

Lightning phenomenon is a peak discharge in which charge accumulated in the clouds discharges into a neighbouring cloud or to the ground. The electrode separation, i.e. cloud-to-cloud or cloud-to-ground is very large, perhaps 10 km or more. The mechanism of charge formation in the clouds and their discharges is quite a complicated and uncertain process. Nevertheless, a lot of information has been collected since the last fifty years and several theories have been put forth for explaining the phenomenon.

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 10^{07} to 10^{5} 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 predominately 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 probable charge distribution model is given in Fig.1 with the corresponding field gradients near the ground.

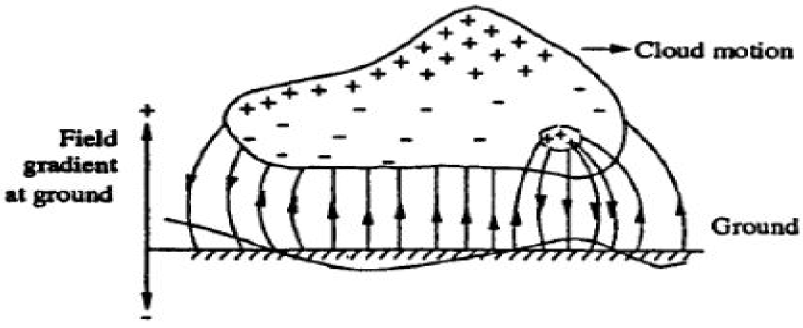


Fig.1Probable field gradient near the ground corresponding to the probable charge distribution in a cloud.

According to the Simpson's theory (Fig. 2) 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 spay in the cloud and negative charge in the air. The spray is blown upwards, but as the velocity of air deceases, 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. 2.

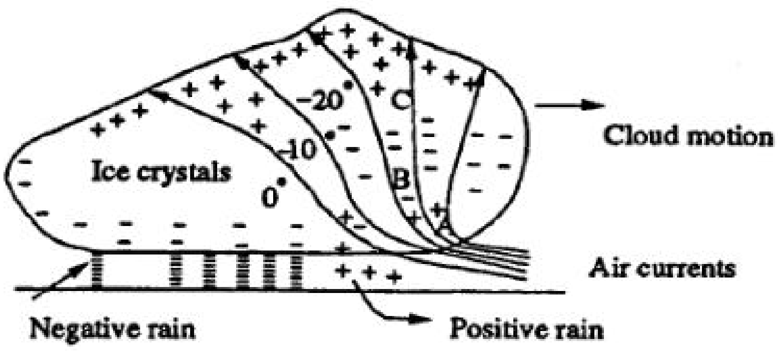


FIG 2 Cloud model according to Simpson's theory

However, the above theory is obsolete and the explanation presented is not satisfactory. Recently, Reynolds and Mason proposed modification, according to which 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°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.

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. Hence, it must be appreciated, that the outer shells of the freeze 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.

According to the Reynolds's theory, which is based on experimental results, the hail packets get negatively charged when impinged upon by warmer ice crystals. When the temperature conditions are reversed, the charging polarity reverses. However, the extent of the charging and consequently the rate of charge generation were found to disagree with the practical observations relating to thunder clouds. This type of phenomenon also occurs in thunder clouds.

Mechanism of Lightning Strokes

When the electric field intensity at some point in the charge concentrated cloud exceeds the breakdown value of the moist ionized air (» 10 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 us, 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 form 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. 3.

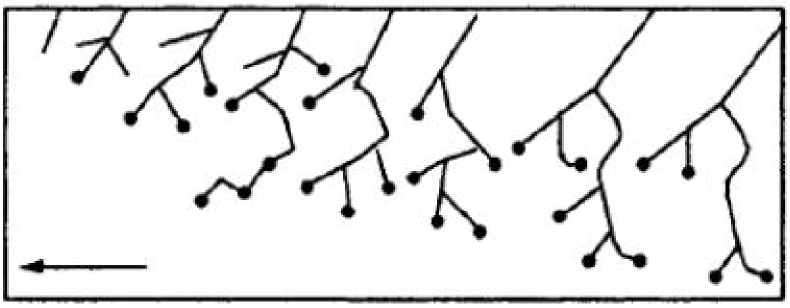


FIG 3 Propagation of a stepped leader stroke from a cloud (• Bright tips recorded)

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 x $1O^7$ cm/s, of the succeeding leader strokes about 10s cm/s, and of the return strokes may be 1.5 x 10^9 to 1.5 x 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 micro-s 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. 4.

FIG 4 Development of the main or return stroke

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

Parameters and Characteristics of the Lightning Strokes

The parameters and characteristics of lightning include the amplitude of the currents, the rate of rise, the probability distribution of the above, and the wave shapes of the lightning voltages and currents. Typical oscillograms of the lightning current and voltage wave shapes on a transmission line are shown in Figs. 4 and 5. The lightning current oscillograms indicate an initial high current portion which is characterized by short front times up to 10 u, s. The high current peak may last for some tens of microseconds followed by a long duration low current portion lasting for several milliseconds. This last portion is normally responsible for damages (thermal damage). Lightning currents are usually measured either directly from high towers or buildings or from the transmission tower legs. The former gives high values and does not present typical currents that occur on electrical transmission lines, and the latter gives inaccurate values due to non-uniform division of current in legs and the presence of ground wires and adjacent towers. Measurements made by several investigators and committees indicated the large strokes of currents (> 100 kA) are possible (Fig. 5). It is known that tall objects attract a large portion of high current strokes, and this would explain the shift of the frequency distribution curves towards higher currents.

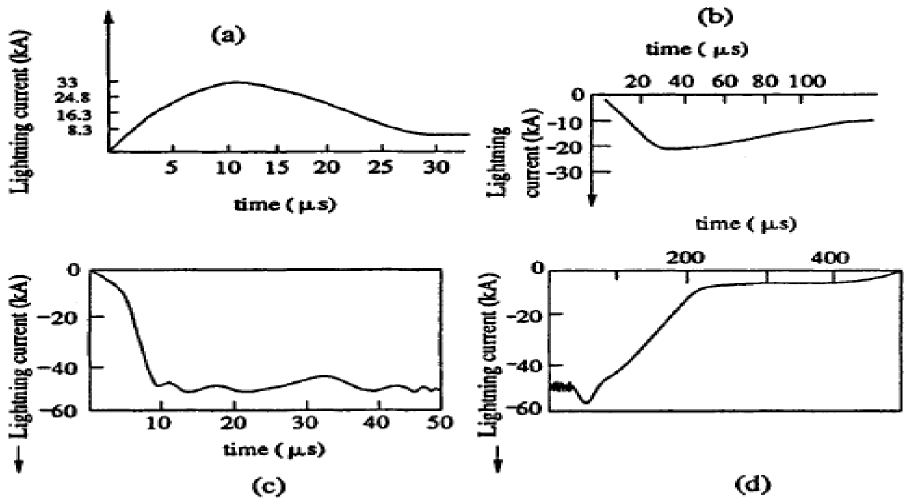


FIG 4:- Typical lightning current oscillograms
(a) to a capacitive balloon (CIGRE)
(b) on Empire State Building (McEachron)
(c) and (d) on transmission line tower (Berger)

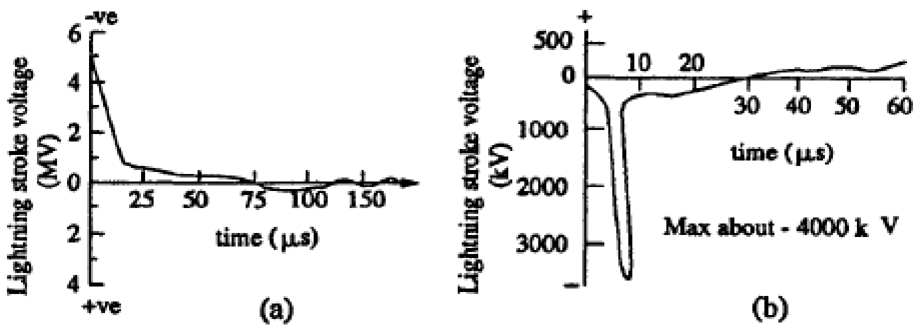


FIG 5 Typical lightning stroke voltage on a transmission line without ground wire

Other important characteristics are time to peak value and its rate of rise. From the field data, it was indicated that 50% of lightning stroke currents have a rate of rise greater than 7.5 kA/µs, and for 10% strokes it exceeded 25 kA/µs The duration of the stroke currents above half the value is more than 30 U. s.

Measurements of surge voltages indicated that a maximum voltage, as high as 5,000 kV, is possible on transmission lines, but on the average, most of the lightning strokes give rise to voltage surges less than 1000 kV on lines. The time to font of these waves varies from 2 to 10 p. s and tail times usually vary from 20 to 100 u. s. The rate of rise of voltage, during rising of the wave may be typically about 1 MV/µs.

Lightning strokes on transmission lines are classified into two groups—the direct strokes and the induced strokes. When a thunder cloud directly discharges on to a transmission line tower or line wires it is called a direct stroke. This is the most severe form of the stroke. However, for bulk of the transmission systems the direct stokes are rare and only the induced strokes occur.

When the thunderstorm generates negative charge at its ground end, the earth objects develop induced positive charges. The earth objects of interest to electrical engineers are transmission lines and towers. Normally, it is expected that the lines are unaffected because they are insulated by string insulators. However, because of high field gradients involved, the positive charges leak from the tower along the insulator surfaces to the line conductors. This process may take quite a long time, of the order of some hundreds of seconds. When the cloud discharges to some earthed object other than the line, the transmission line is left with a huge concentration of charge (positive) which cannot leak suddenly. The transmission line and the ground will act as a huge capacitor charged with a positive charge and hence overvoltages occur due to these induced charges. This would result in a stroke and hence the name "induced lightning stroke".

Sometimes, when a direct lightning strike occurs on a tower, the tower has to carry huge impulse currents. If the tower fooling resistance is considerable, the potential of the tower rises to a large value, steeply with respect to the line and consequently a flashover may take place along the insulator stings. This is known as back flashover.

Origin of Switching Surges

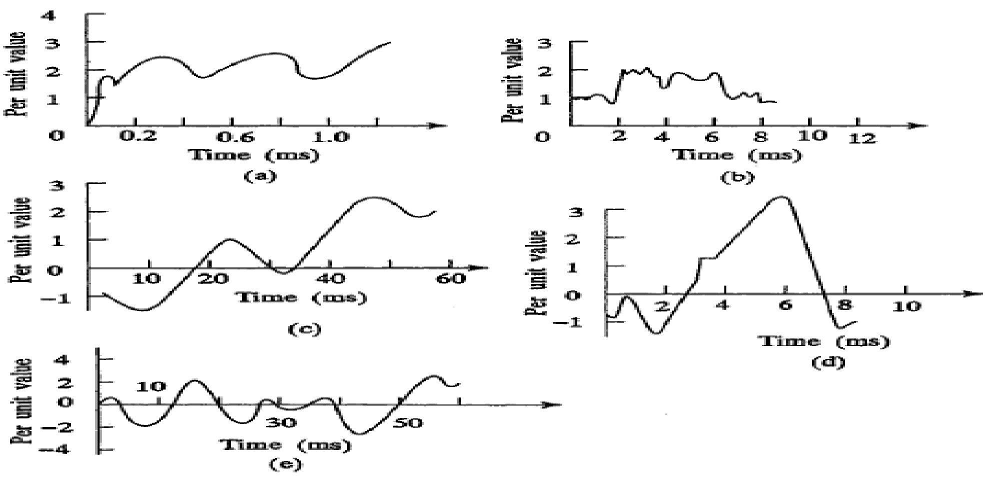
The making and breaking of electric circuits with switchgear may result in abnormal overvoltages in power systems having large inductances and capacitances. The overvoltages may go as high as six times the normal power frequency voltage. In circuit breaking operation, switching surges with a high rate of rise of voltage may cause repeated restriking of the arc between the contacts of a circuit breaker, thereby causing destruction of the circuit breaker contacts. The switching surges may include high natural frequencies of the system, a damped normal frequency voltage component, or the restriking and recovery voltage of the system with successive reflected waves form 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.

(i) Disconnection of unloaded transformers, reactors, etc.
(ii) Energization or reclosing of lines and reactive loads.
(iii) Sudden switching off of loads.
(iv) Short circuits and fault clearances.
(v) Resonance phenomenon like ferro-resonance, arcing grounds, etc.

Typical wave shapes of the switching surges are given in **Figs. 6a to (e).**



a) Recovery voltage after fault clearing
(b) Fault initiation
(c) Overvottage at the line end after fault clearing
(d) Energization of long transmission line
(e) Overvoltage at line end during (d)

FIG 6 :-Typical waveshapes of switching surge voltages

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.

Switching Overvoltages in EHV and UHV Systems

The insulation has the lowest strength for switching surges with regard to long air gaps. Further, switching overvoltages are of relatively higher magnitudes as compared to the lightning overvoltages for 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). The different situations under which this happens are summarised as

(i) interruption of low inductive currents (current chopping) by high speed circuit breakers. This occurs when the transformers or reactors are switched off.
(ii) interruption of small capacitive currents, such as switching off of unloaded lines etc.
(iii) ferro-resonance condition
This may occur when poles of a circuit breaker do not close simultaneously
(iv) energization of long EHV or UHV lines.

Transient overvoltages in the above cases can be of the order of 2.0 to 3.3 p.u. and will have magnitudes of the order of 1200 kV to 2000 kV on 750 kV systems. The duration of these overvoltages varies from 1 to 10 ms depending on the circuit parameters. It is seen that these are of comparable magnitude or are even higher than those that occur due to lightning. Sometimes the overvoltages may last for several cycles. The other situations of switching that give rise to switching overvoltages of shorter duration (0.5 to 5 ms) and lower magnitudes (2.0 to 2.5 p.u.) are:

(a) single pole closing of circuit breaker
(b) interruption of fault current when the L-G or L-L fault is cleared
(c) resistance switching used in circuit breakers
(d) switching lines terminated by transformers
(e) series capacitor compensated lines
(f) sparking of the surge diverter located at the receiving end of the line to limit the lightning overvoltages

The overvoltages due to the above conditions are studied or calculated from

(a) mathematical modelling of a system using digital computers
(b) scale modelling using transient network analysers
(c) by conducting field tests to determine the expected maximum amplitude of the overvoltages and their duration at different points on the line.

The main factors that are investigated in the above studies are

(i) the effect of line parameters, series capacitors and shunt reactors on the magnitude and duration of the transients
(ii) the damping factors needed to reduce the magnitude of overvoltages
(iii) the effect of single pole closing, restriking and switching with series resistors or circuit beakers on the overvoltages, and
(iv) the lightning arrester spark over characteristics.

It is necessary in EHV and UHV systems to control the switching surges to a safe value of less than 2.5 p.u. or preferably to 2.0 p.u. or even less. The measures taken to control or reduce the overvoltages ae

(i) one step or multi-step energization of lines by pre-insertion of resistors,
(ii) phase controlled closing of circuit breakers with proper sensors,
(iii) drainage of trapped charges on long lines before the reclosing of the lines, and
(iv) limiting the overvoltages by using surge diverters.

Power Frequency Overvoltages in Power Systems

The power frequency overvoltages occur in large power systems and they are of much concern in EHV systems, i.e. systems of 400 kV and above. The main causes for power frequency and its harmonic overvoltages are

(a) sudden loss of loads,
(b) disconnection of inductive loads or connection of capacitive loads,
(c) Ferranti effect, unsymmetrical faults, and
(d) saturation in transformers, etc.

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

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

(a) Sudden Load Rejection

Sudden load rejection on large power systems causes the speeding up of generator prime movers. The speed governors and automatic voltage regulators will intervene to restore normal conditions. But initially both the frequency and voltage increase. The approximate voltage rise, neglecting losses, etc. may be taken as

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

where xs is the reactance of the generator (= the sum of the transient reactances of the generator and the transformer), xc is the capacitive reactance of the line at open end at increased frequency, Ef the voltage generated before the over-speeding and load ejection,/is the instantaneous increased frequency, and/n is the normal frequency.

This increase in voltage may go to as high as 2.0 per unit (p.u.) value with 400 kV lines. The voltage at the sending end is affected by the line length, short circuit MVA at sending end bus, and reactive power generation of the line (due to line capacitive reactance and any shunt or series capacitors). Shunt reactors may reduce the voltage to 1.2 to 1.4 p.u.

(b) Ferranti Effect

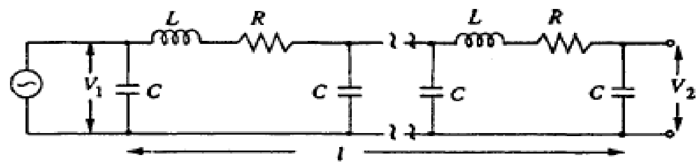
Long uncompensated transmission lines exhibit voltage rise at the receiving end. The voltage rise at the receiving end V2 is approximately given by

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

where, V_1 = sending end voltage,
l = length of the line,
β = phase constant of the line

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

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



L, R and C — Inductance, resistance and capacitance per unit length of the line
l — Length of the line

FIG 7 Typical uncompensated long transmission line

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

$$I_C \approx j\omega C V_1 = \frac{V_1}{X_C}$$

and the voltage $V_2 \approx V_1 \left[1 - \frac{X_L}{2X_C} \right]$

where, X_L = line inductive reactance, and

X_C = line capacitive reactance.

The line distributed parameters *R, L, G* and C per unit length are known.

(c) Ground Faults and Their Effects

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

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

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

(d) Saturation Effects

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

Control of Overvoltages Due to Switching

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

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

(a) Insertion of Resistors

It is normal and a common practice to insert resistances in series with circuit beaker contacts when switching on but short circuiting them after a few cycles. This will reduce the transients occurring due to switching. The voltage step applied is first reduced to ZqI(R + Zq) per unit where Zo is the surge impedance of the line. It is effected from the far end unchanged and again reflected back from the near end with election factor (R - Zq)I(R + Zq) per unit. If R = Zq, thee is no election from the far end. The applied step at the first instance is only 0.5 per unit.

When the resistor is short circuited, a voltage step equal to the instantaneous voltage drop enters the line. If the resistor is kept for a duration larger than 5ms (for 50 Hz sine wave = 1/4 cycle duration), it can be shown from successive reflections and transmissions, that the overvoltage may reach as high as 1.2 p.u. for a line length of 500 km. But for conventional opening of the breaker, the resistors have too high an ohmic value to be effective for resistance closing. Therefore, pe-inscrtion of suitable value resistors in practice is done to limit the overvoltage to less than 2.0 to 2.5 p.u. Normal time of insertion is 6 to 10 m s.

(b) Phase Controlled Switching

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

(c) Drainage of Trapped Charge

When lines are suddenly switching off, "electric charge" may be left on capacitors and line conductors. This charge will normally leak through the leakage path of the insulators, etc. Conventional potential transformers (magnetic) may also help the drainage of the charge. An effective way to educe the trapped charges during the lead time before reclosing is by temporary insertion of resistors to ground or in seires with shunt reactors and removing before the closure of the switches.

(d) Shunt Reactors

Normally all EHV lines will have shunt reactors to limit the voltage rise due to the Ferranti effect. They also help in reducing surges caused due to sudden energizing. However, shunt reactors cannot drain the trapped charge but will give rise to oscillations with the capacitance of the system. Since the compensation given by the reactors will be less than 100%, the frequency of oscillation will be less than the power frequency and overvoltages produced may be as high as 1.2 p.u. Resistors in series with these reactors will suppress the oscillations and limit the overvoltages.

Protection of Transmission Lines against Overvoltages

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. Switching surges and power frequency overvoltages are accounted for by providing greater insulation levels and with proper insulation co-ordination. Hence, the above two protection schemes are dealt with separately in the next two sections.

Protection against Lightning Overvoltages and Switching Surges of short Duration

Overvoltages due to lightning strokes can be avoided or minimized in practice by

(a) shielding the overhead lines by using ground wires above the phase wires,

(b) using ground rods and counter-poise wires, and

(c) including protective devices like expulsion gaps, protector tubes on the lines, and surge diverters at the line terminations and substations.

(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. The arrangements of ground rise over the line conductor is shown in Fig.below

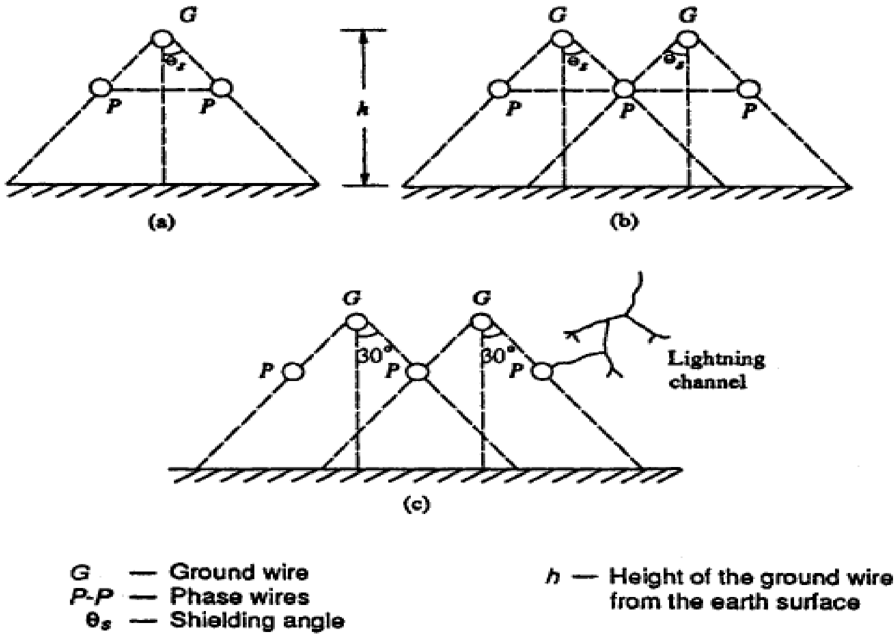


FIG 8 Shielding arrangement of overhead lines by ground wires

The mechanism by which the line is protected may be explained as follows. If a positively charged cloud is assumed to be above the line, it induces a negative charge on the portion below it, of the transmission line. With the ground wire present, both the ground wire and the line conductor get the induced charge. But the ground wire is earthed at regular intervals, and as such the induced charge is drained to the earth potential only; the potential difference between the ground wire and the cloud and that between the ground wire and the transmission line wire will be in the inverse ratio of their respective capacitances [assuming the cloud to be a perfect conductor and the atmospheric medium (air) a dielectric]. As the ground wire is nearer to the line wire, the induced charge on it will be much less and hence the potential rise will be quite small. The effective protection or shielding given by the ground wire depends on the height of the ground wire above the ground (h) and the protection or shielding angle 0S (usually 30°) as shown in Fig. 8.
The shielding angle 65 « 30° was considered adequate for tower heights of 30 m or less. The shielding wires may be one or more depending on the type of the towers used. But for EHV lines, the tower heights may be up to 50 m, and the lightning strokes sometimes occur directly to the line wires as shown in Fig. 8. The present tend in fixing the tower heights and shielding angles is by considering the "flashover rates" and failure probabilities.

(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, (6) 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

$$V_T = \frac{I_0 Z_T}{\left(1 + \frac{Z_T}{Z_S}\right)}$$

where,

Z_T= surge impedance of the tower, and Z_S= surge impedance of the ground wire.

If the surge impedance of the tower, which is the effective tower footing resistance, is reduced, the surge voltage developed is also reduced considerably. This is accomplished by providing driven ground rods and counter-poise wires connected to tower legs at the tower foundation.

Ground rods are a number of rods about IS mm 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 spacings 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 10 *fl*

The above effect is alternatively achieved by using counter-poise wires. Counterpoise wires are wires 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 25 *£1*. The depth does not materially affect the resistance of the counter-poise, and it is only necessary to bury it to a depth enough to prevent theft. It is desirable to use a larger number of parallel wires than a single wire. But it is difficult to lay counter-poise wires compared to ground or driven rods.

(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. Line terminations, junctions of lines, and sub-stations are usually fitted with surge diverters.

(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 break over due to overvoltages. A typical such arrangement is shown in Fig. below.

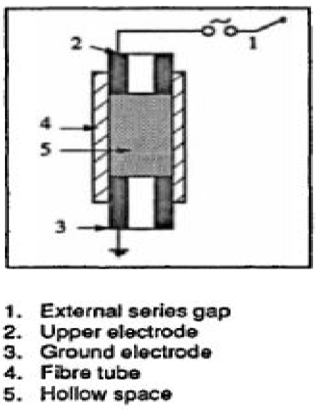


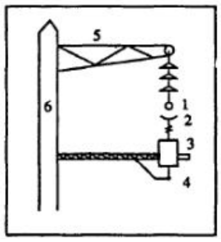
FIG Expulsion gap

This essentially consists of a rod gap in air in series with a second gap enclosed within a fiber 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 fiber tube due to lightning current vaporizes a small portion of the fiber material. The gas thus produced, being a mixture of water vapor and the decomposed fiber product, drive away the arc products and ionized air. When the follow-on power frequency current passes through zero value, the arc is extinguished and the path becomes open circuited. Meanwhile the insulation recovers its dielectric strength, and the normal conditions are established. The lightning and follow-up power frequency currents together can last for 2 to 3 half cycles only. Therefore, generally no disturbance in the network is produced.

For 132 or 220 kV lines, the maximum current rating may be about 7,500 A.

(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.



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

FIG :- Protector tube mounting

The hollow gap in the expulsion tube is replaced by a nonlinear element which offers a very high impedance at low currents but has low impedance for high or lightning currents. When an overvoltage occurs and the spark gap 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.

(iii) Rod gaps

A much simpler and effective protective device is a rod-gap . However, it does not meet the complete requirement. The spark over voltage of a rod gap depends on the atmospheric conditions. A typical volt-time characteristic of a 67 cm-rod gap is shown in Fig., with its protective margin. There is no current limiting device provided so as to limit the current after spark over, 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. Nevertheless, rod gaps do provide efficient protection where thunderstorm activity is less and the lines are protected by ground wires.

(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. These are capable of discharging 10 to 20 kA of long duration surges (8/20 p. s) and 100 to 250 kA of the short duration surge currents (1/5 *JL* s).

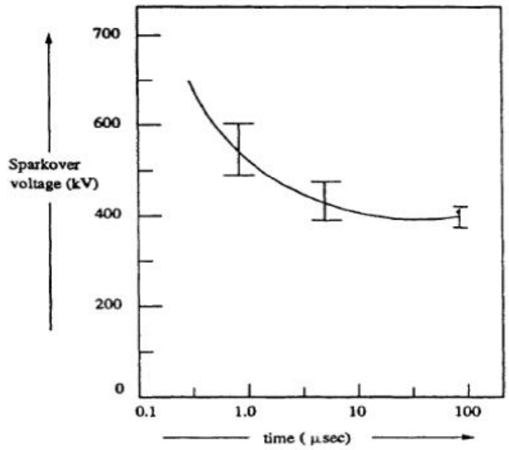


FIG Volt-time characteristic of a standard rod-rod gap

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